Thermal Effects on Nonthermal Species

Michael Ratz

August 21 2023

supported by NSF

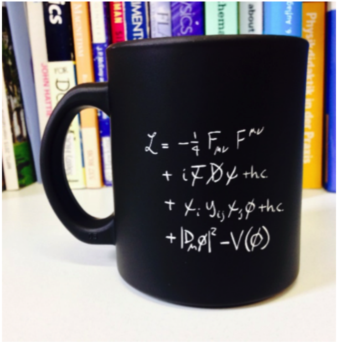
Based on:

- W. Buchmüller, K. Hamaguchi, O. Lebedev & M.R. Nucl. Phys. B699, 292-308 (2004)
- B. Lillard, M.R., T. Tait & S. Trojanowski JCAP 1807 no. 07, 056 (2018)
- V. Knapp–Pérez, G. Mohlabeng, M.R. & T. Tait, in preparation

Disclaimers and apologies

- very little citations
- many cartoons

Main message



https://home.cern/news/news/cern/sit-down-coffee-standard-model

- ☞ standard model (SM) particles interact via gauge and Yukawa couplings

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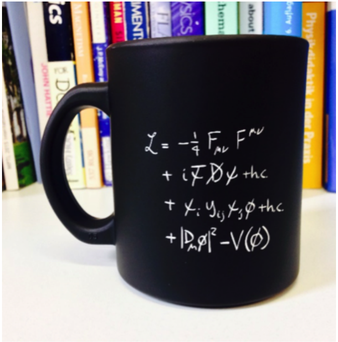

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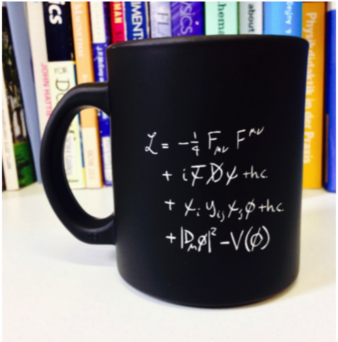

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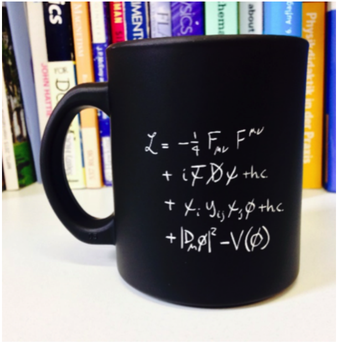

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Main message of this talk

"equilibrium–style" thermodynamics can be particularly important for nonequilibrated species

Overview

☞ couplings may not be God–given but consequence of some dynamics

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- ☞ consider field–dependent couplings/masses

$$g = g(S/\Lambda)\ , \quad y = y(S/\Lambda) \quad \text{and/or} \quad m = m(S) \sim \lambda\, S$$

weakly coupled scalar (modulus, flavon, dark scalar . . .)

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  - in SUSY models often $m_S \sim m_{3/2} \overset{?}{\sim} \mathrm{TeV}$

gravitino mass

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e.g. Bauer, Schell & Plehn (2016)

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purpose of this talk:

discuss weakly coupled scalars in the hot early universe

Thermal potential

of

weakly coupled scalars

Main focus of this talk

☞ what can we say about field-dependent couplings at high T?

temperature

Main focus of this talk

- what can we say about field-dependent couplings at high T?

see lectures by Joe Davighi for many more applications of anomalies

- one can figure this out using anomalies. . .

Buchmüller, Hamaguchi & MR (2003)

Main focus of this talk

☞ what can we say about field-dependent couplings at high T?

☞ …but it is more convenient to consider free energy

Fardon, Nelson & Weiner (2004); Buchmüller, Hamaguchi, Lebedev & MR (2004); Lillard, MR, Tait & Trojanowski (2018)

$$\mathcal{F} = \mathcal{F}(T, S)$$

$$\simeq -\frac{\pi^2}{90} g_* T^4 + T^2 \left(\sum_i c_i^{(g)} g_i^2(S) + \sum_f c_f^{(y)} y_f^2(S) + \sum_j c_j^{(m)} m_j^2(S) \right)$$

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gauge factors

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fermions

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degrees of freedom

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where

$$c^{(g)} = \frac{T^2}{64\pi^2} (N_c^2 - 1)(N_c + 3N_f) \quad \text{for } \mathrm{SU}(N_c)$$

# of colors

# of flavors

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$$c_j^{(m)} = \frac{1}{24} \quad \text{e.g. if} \qquad m_j = h_j\, S$$

$$\curvearrowright \quad \Delta\mathcal{F} = \frac{|h_j|^2}{24}\, T^2\, S^2 \quad \text{for a boson}$$

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➥ free energy "wants" couplings and masses small

S–dependence of free energy

- dependence of free energy on mass of a boson/fermion

Dolan & Jackiw (1974); Fardon, Nelson & Weiner (2004);... Batell & Ghalsasi (2023)

$$\delta\mathcal{F} = -\frac{\nu}{2\pi^2} T^4 \, J_{B/F}\left(\frac{m^2(S)}{T^2}\right)$$

#(d.o.f.)

$$J_{B/F}(y^2) = \int\limits_0^\infty \mathrm{d}x \, x^2 \, \ln\left[1 \mp \mathrm{e}^{-\sqrt{x^2+y^2}}\right]$$

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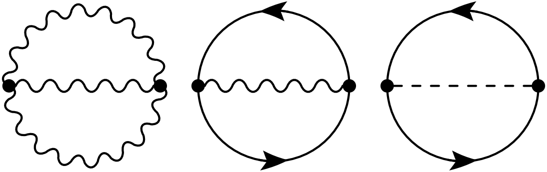

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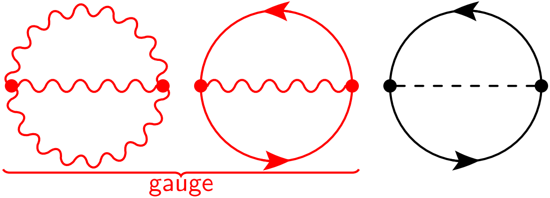

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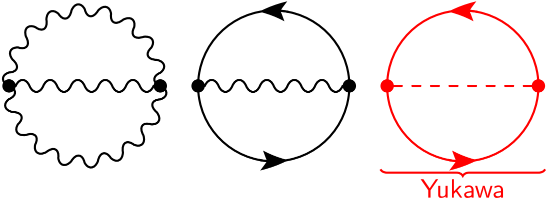

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$\alpha_2 = \frac{3}{196}(N_C^2-1)\,(N_C+3N_F)$ for $\mathrm{SU}(N_C)$ w/ N_F fundamentals

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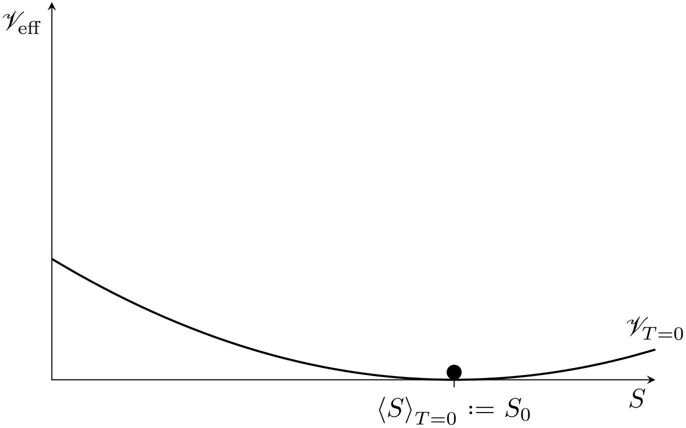

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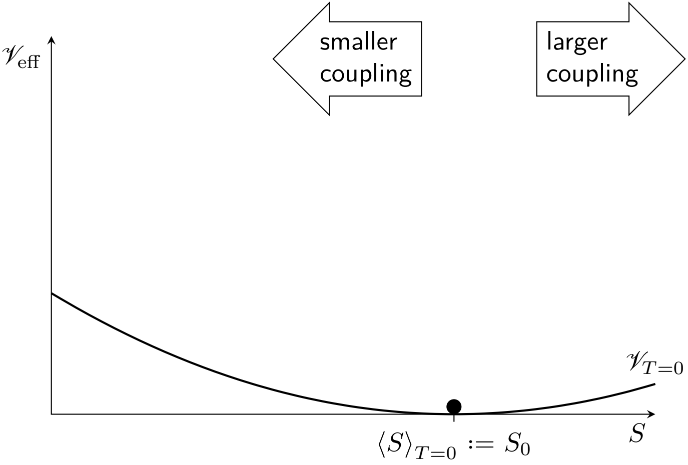

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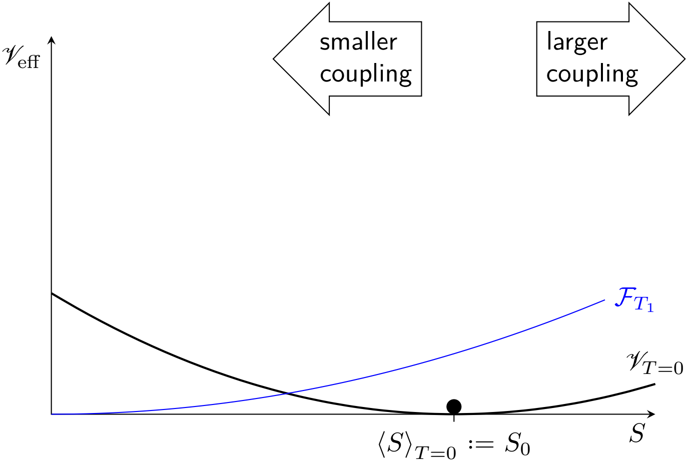

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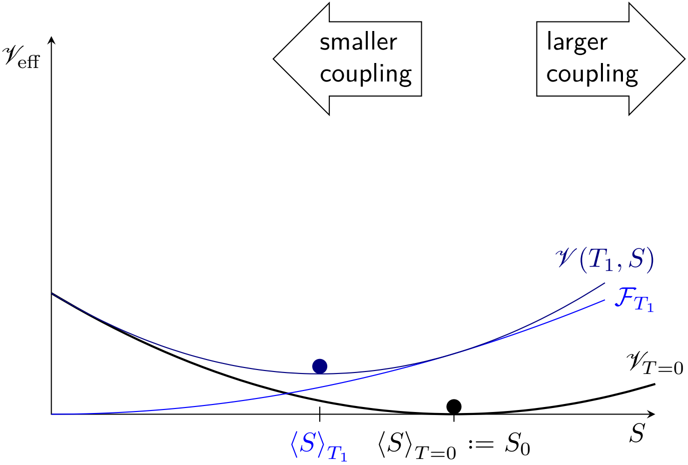

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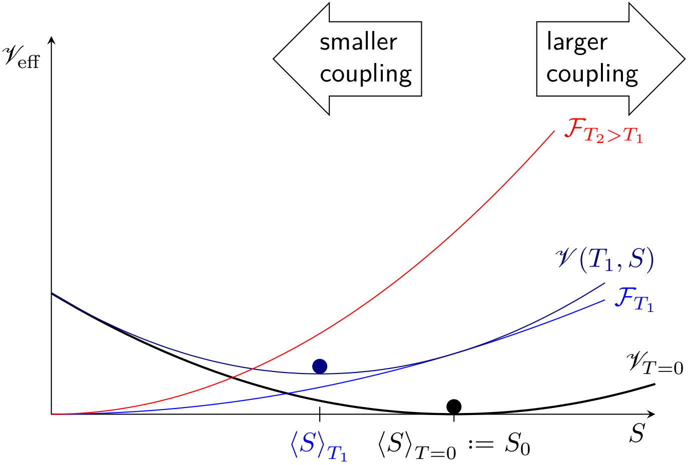

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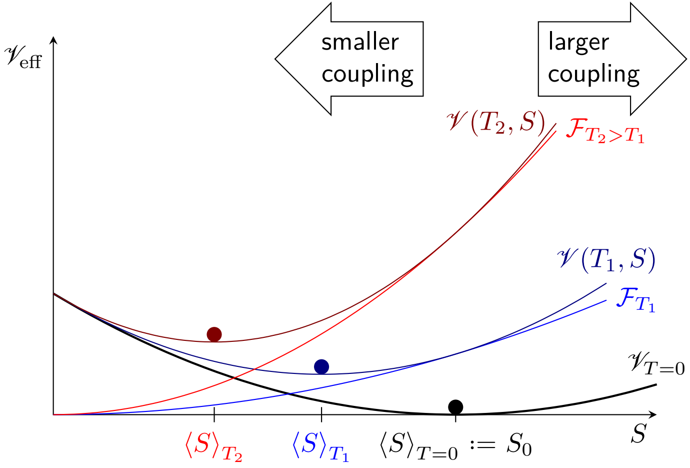

Implications

☞ couplings at high temperature

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Implications

- couplings at high temperature
- moduli problems
- flavon dynamics

Gauge couplings at high temperature

☞ common relation between gauge coupling and dilaton

$$\frac{S}{\Lambda} = \frac{1}{g^2}$$

in strings: $\Lambda = M_\mathsf{P}$

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- ☞ competition between zero–temperature potential and free energy

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- gauge couplings turn essentially off at T_*

Dilaton destabilization

at

high temperature

Dilaton destabilization at high temperature

Buchmüller, Hamaguchi, Lebedev & MR (2004)

- typical dilaton potential: $g^2 = 1/S$

S is real part of stringy dilaton

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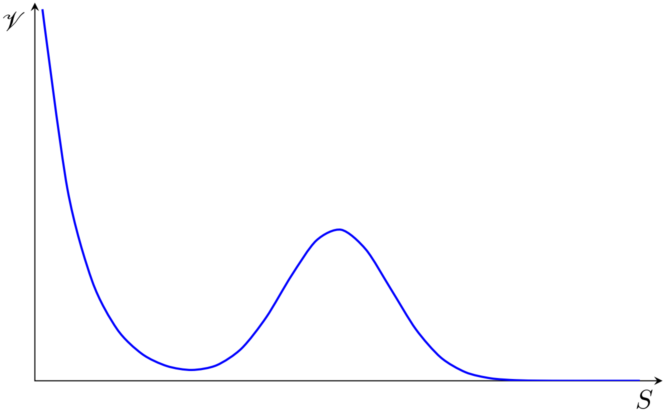

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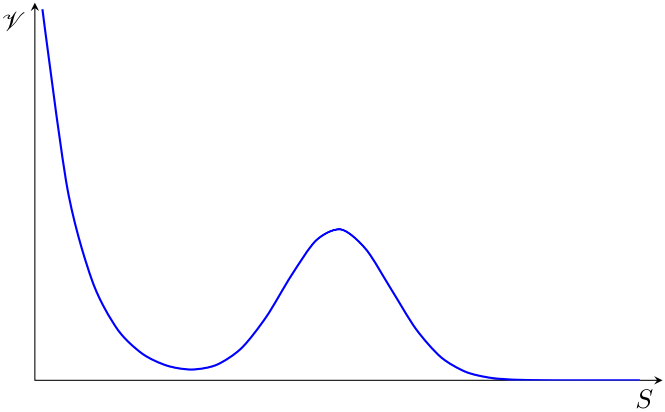

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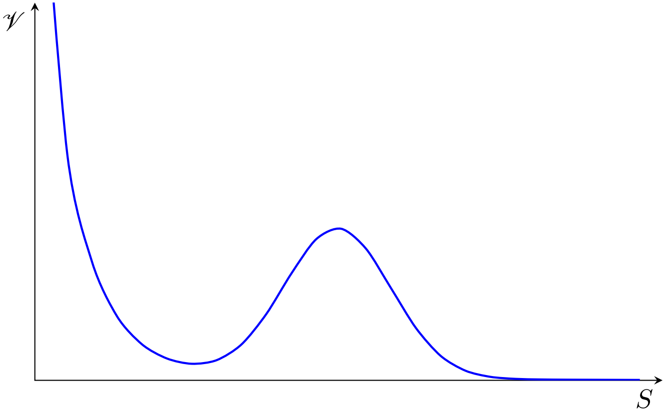

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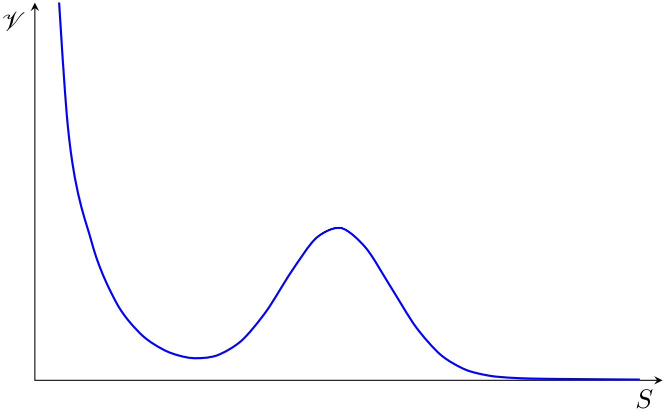

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Dilaton destabilization at high temperature

Buchmüller, Hamaguchi, Lebedev & MR (2004)

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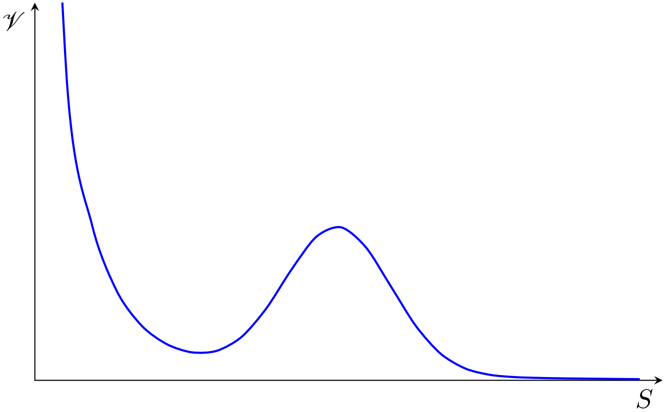

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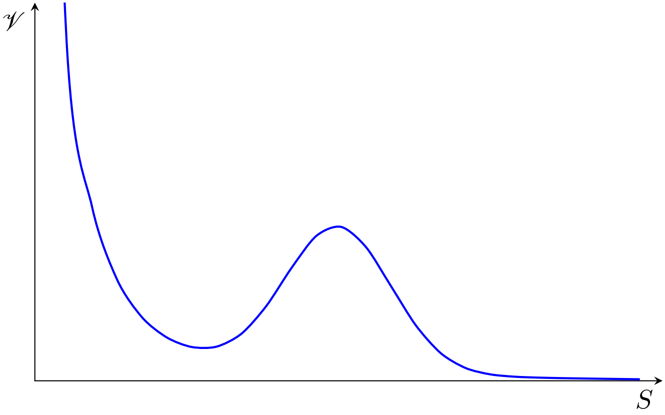

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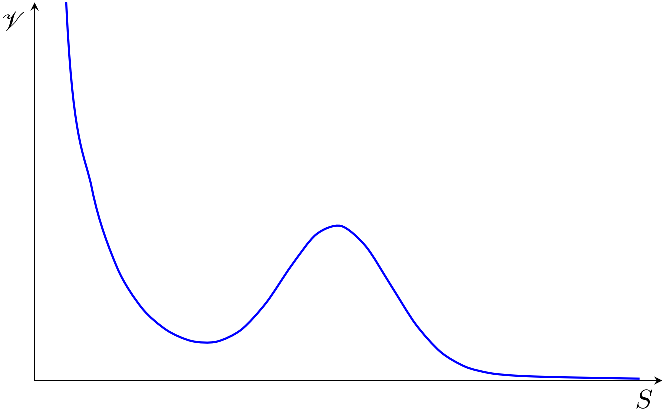

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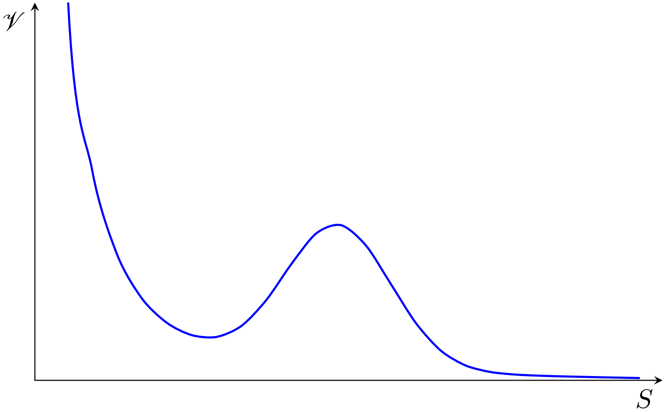

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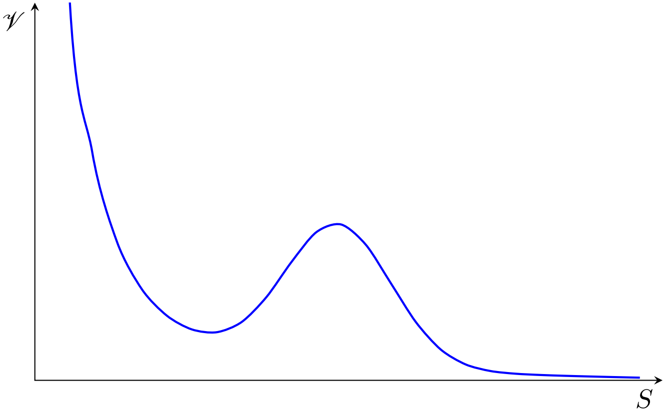

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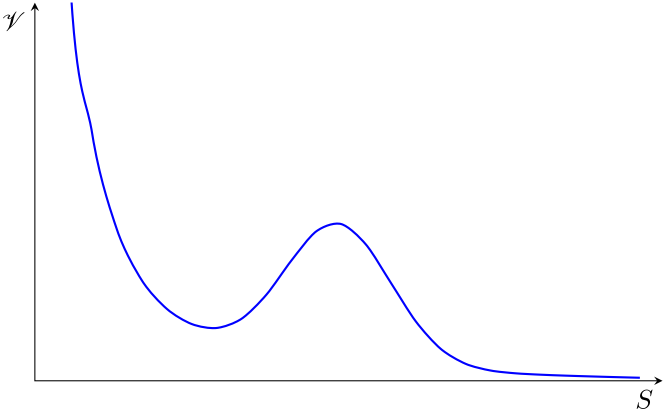

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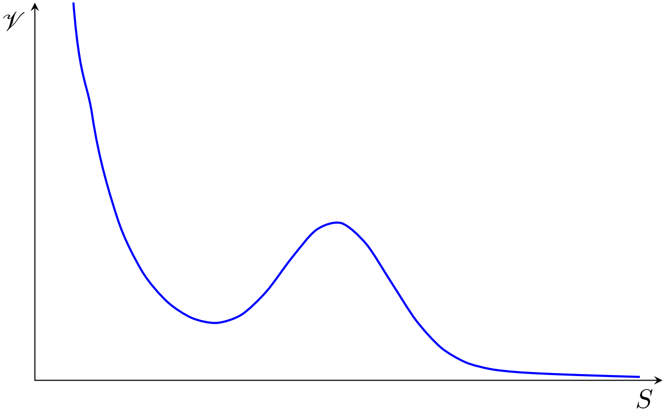

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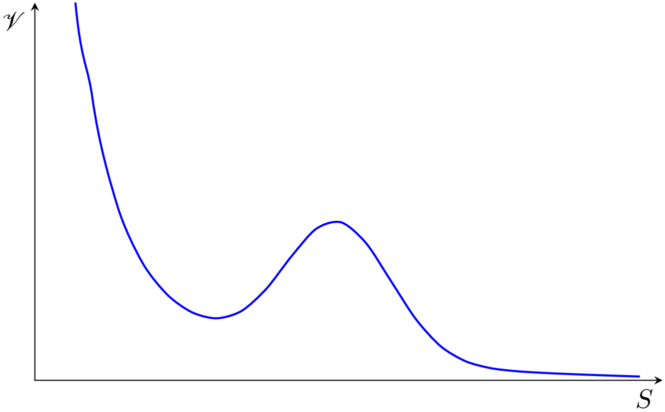

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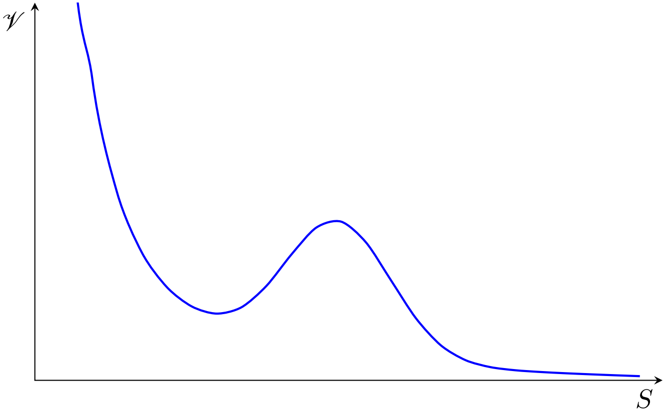

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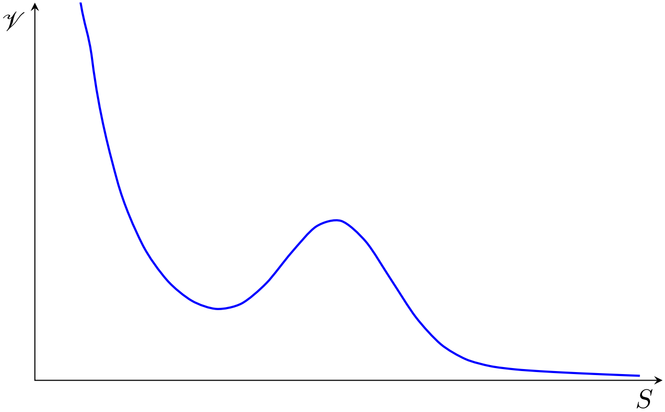

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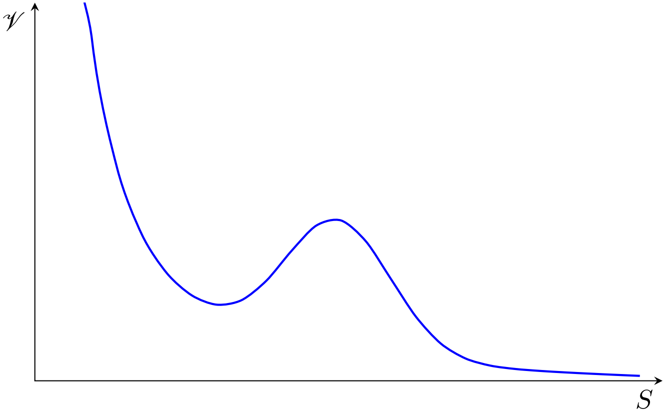

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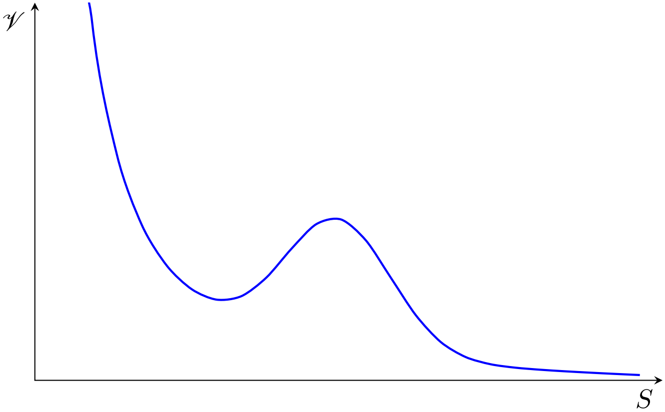

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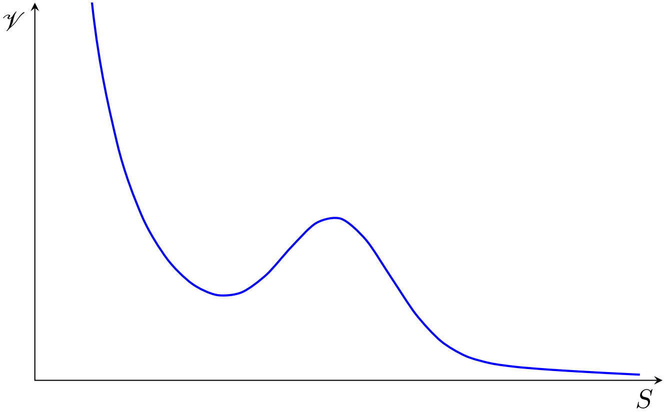

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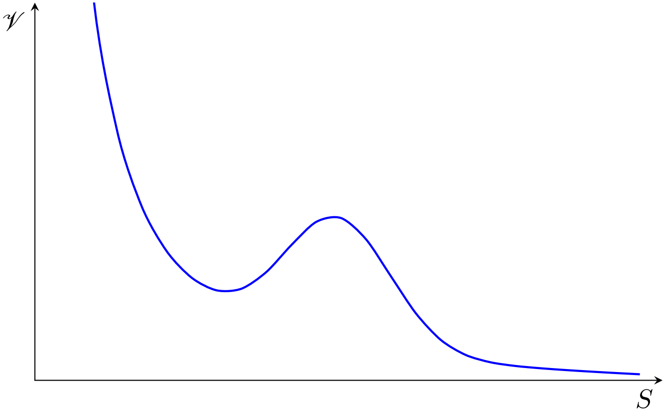

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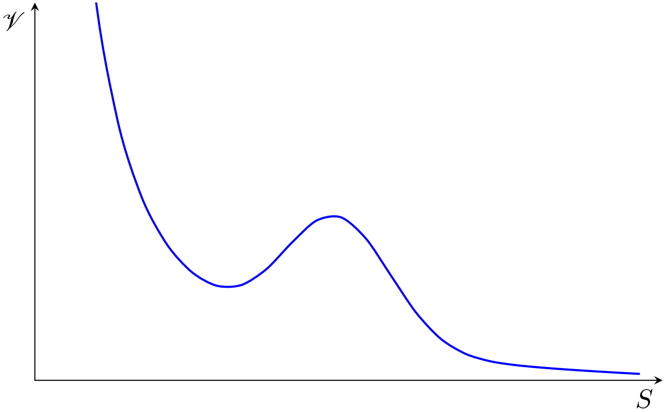

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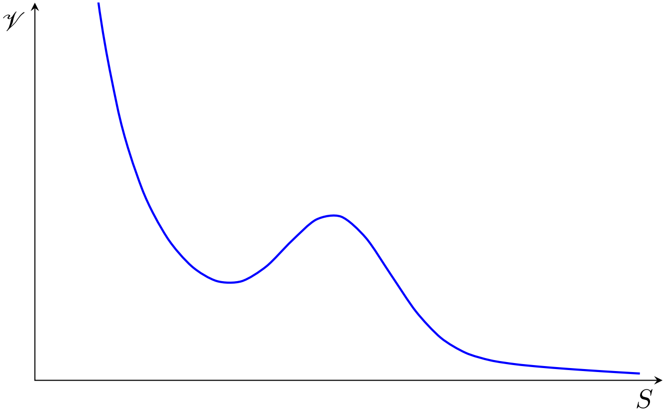

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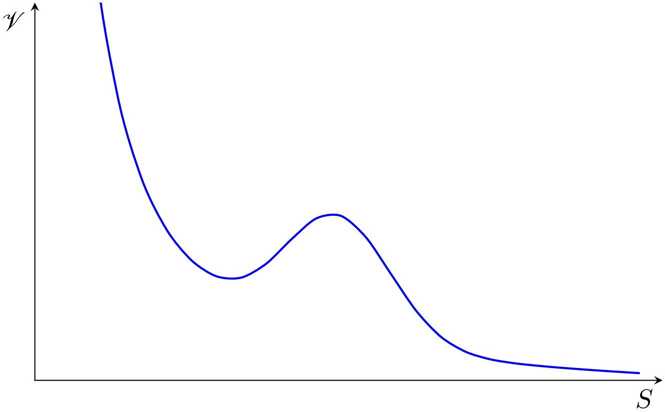

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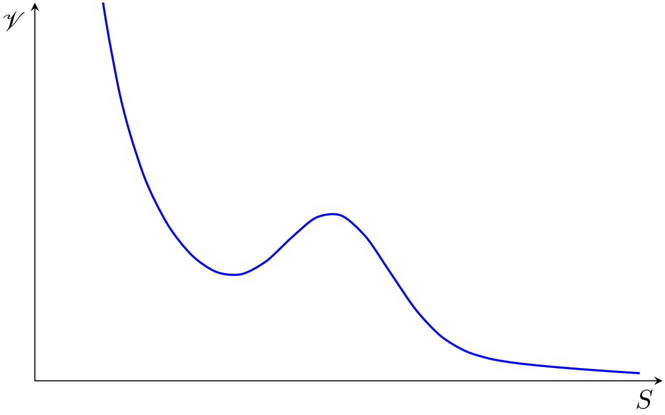

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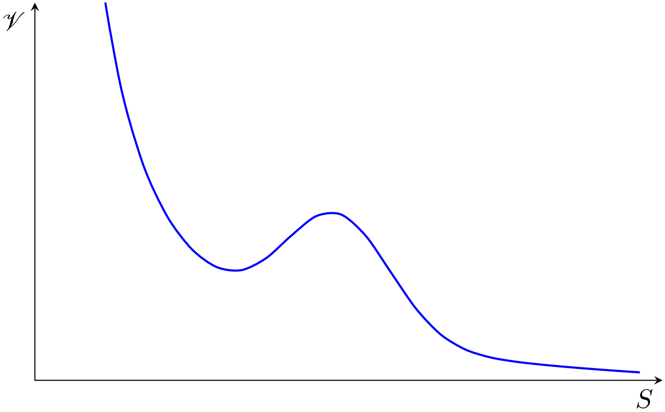

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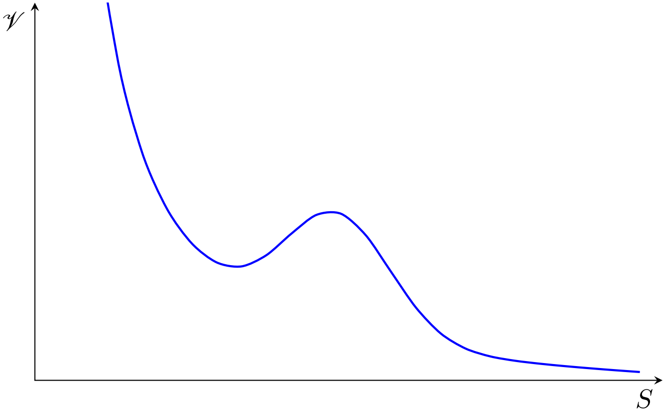

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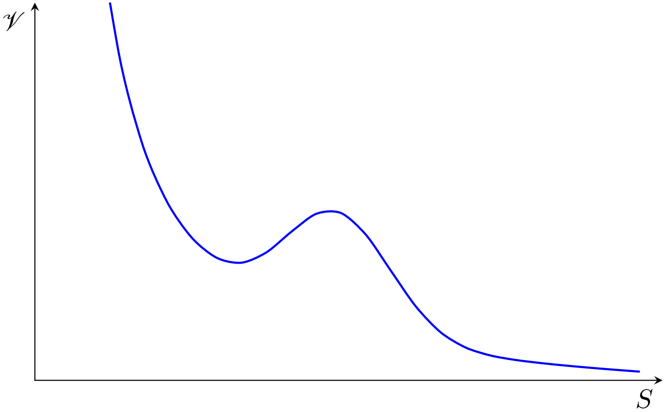

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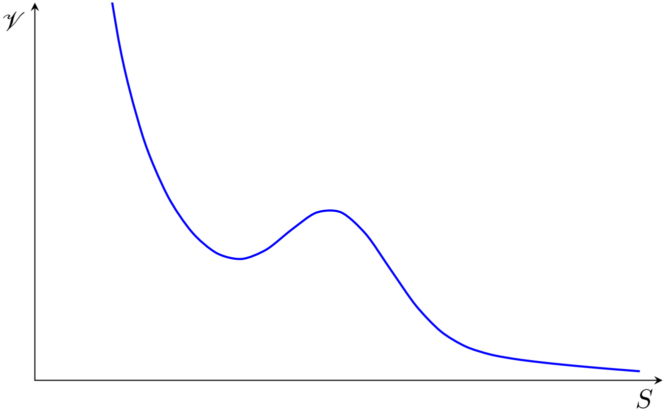

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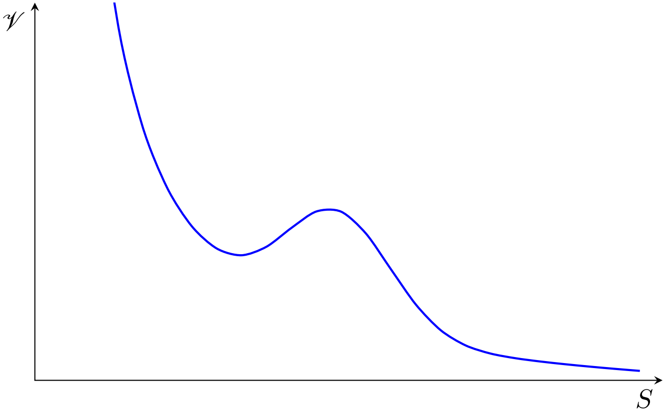

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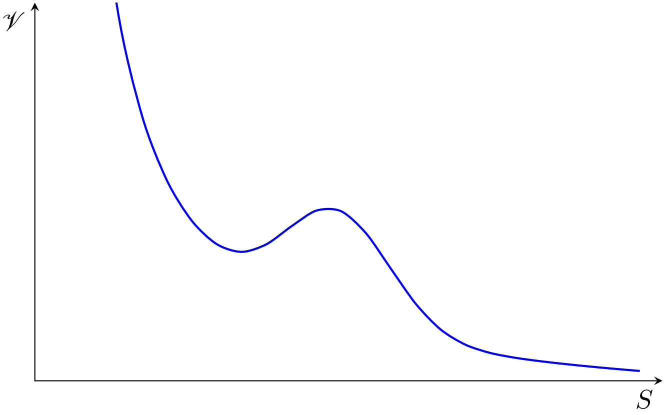

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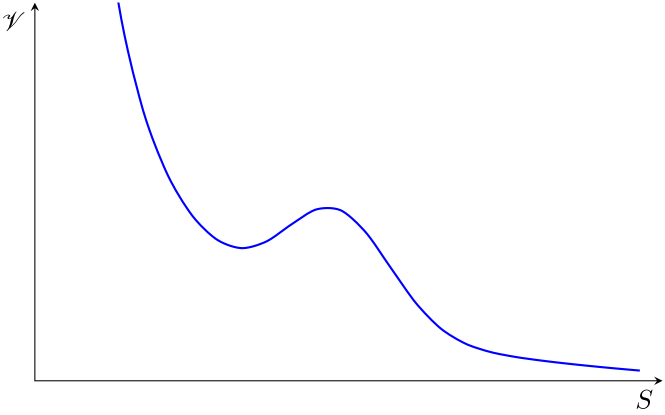

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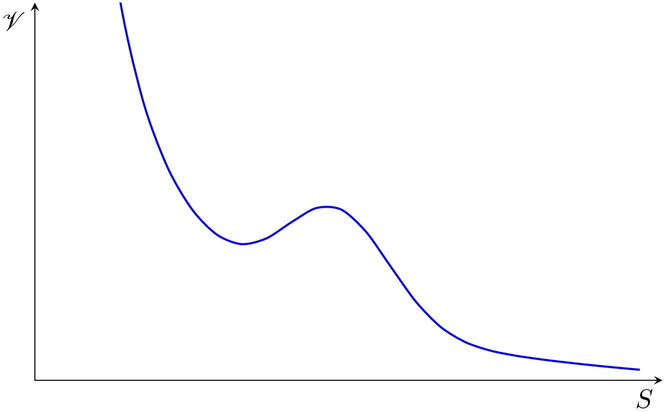

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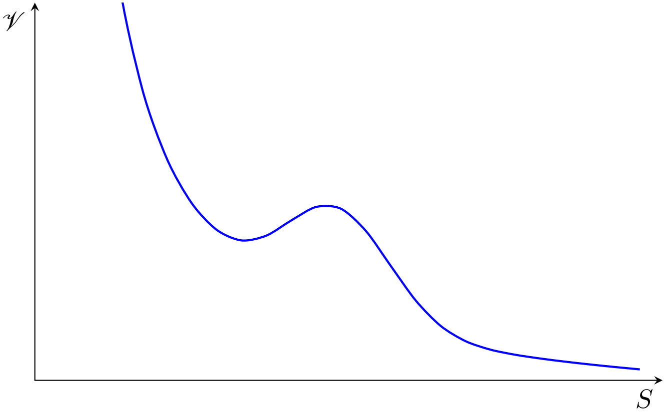

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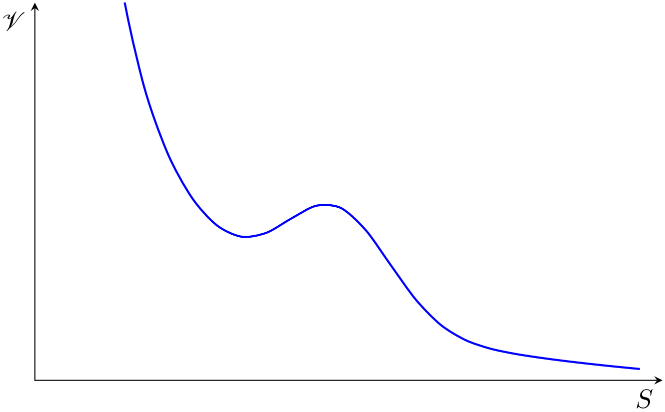

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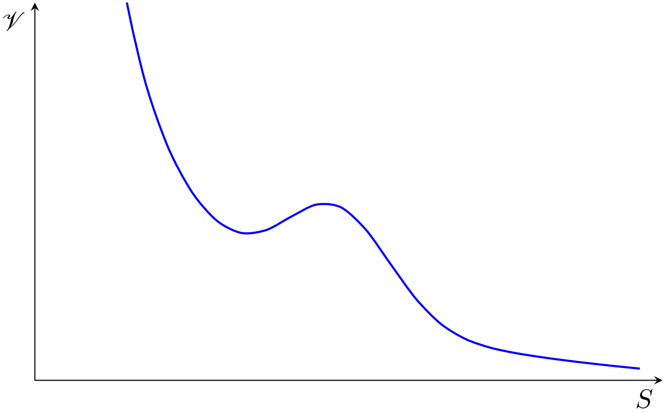

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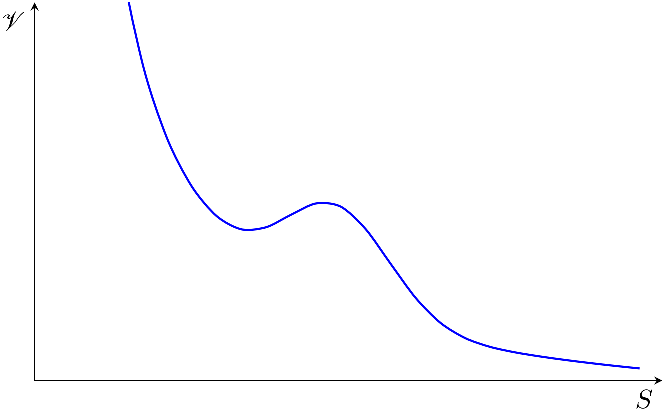

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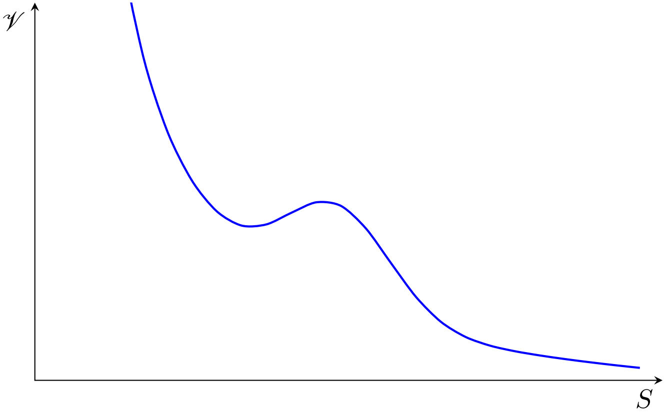

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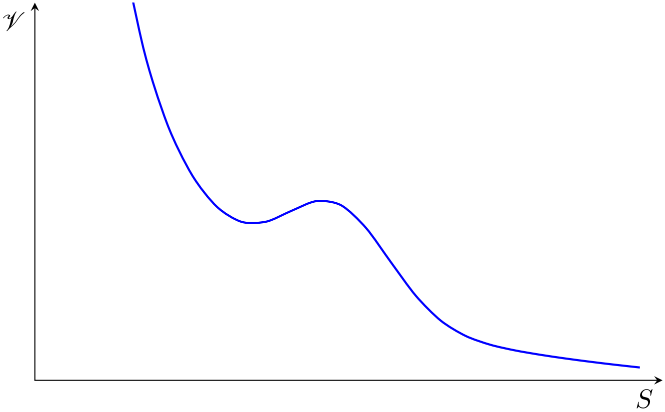

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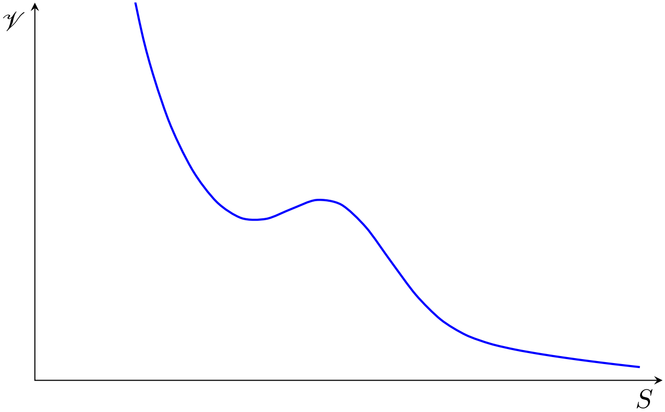

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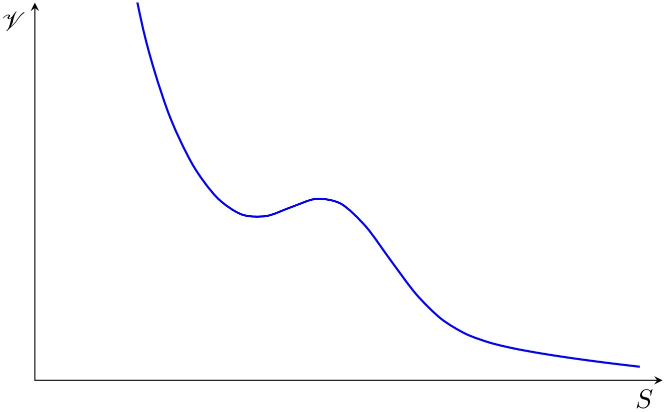

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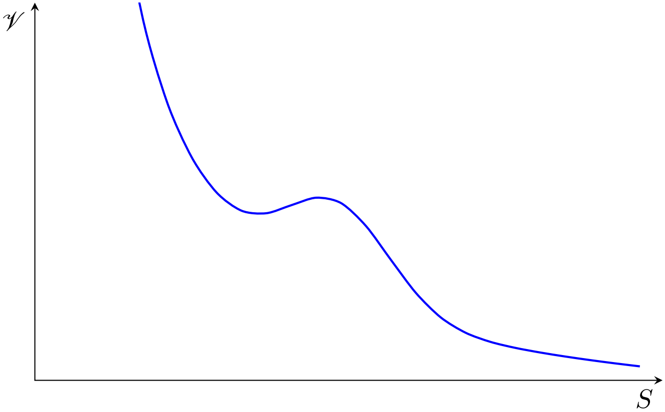

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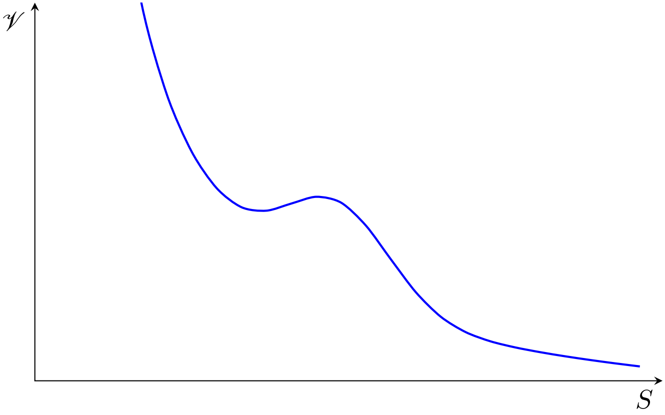

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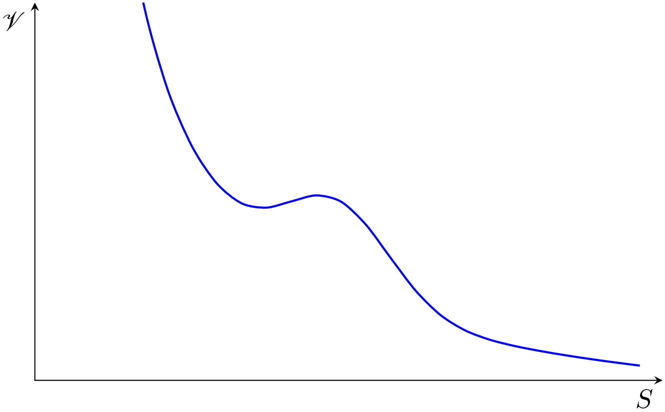

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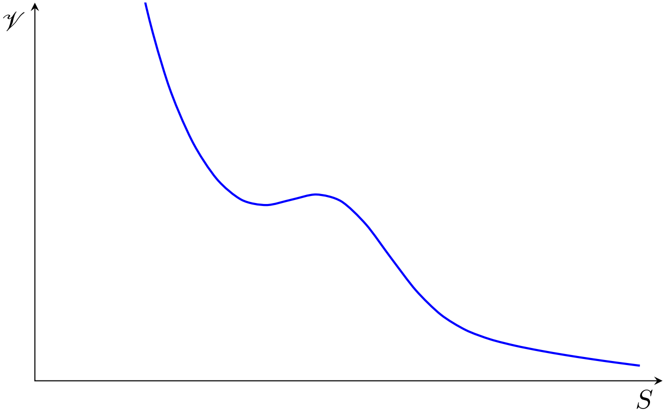

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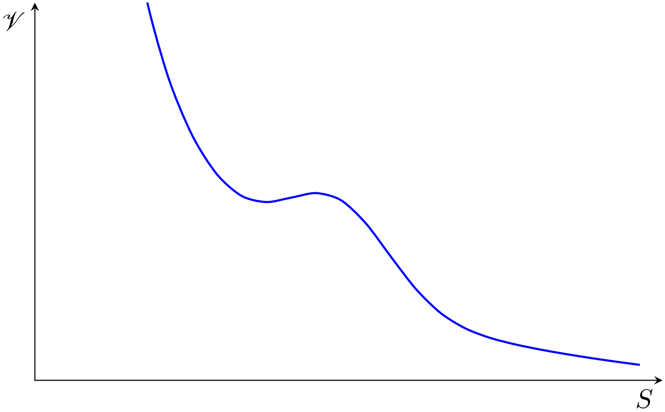

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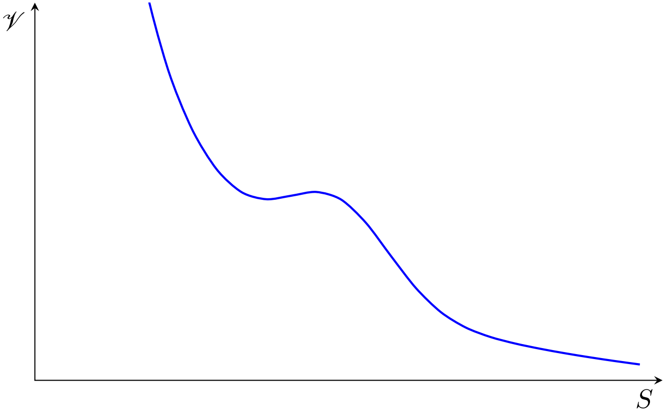

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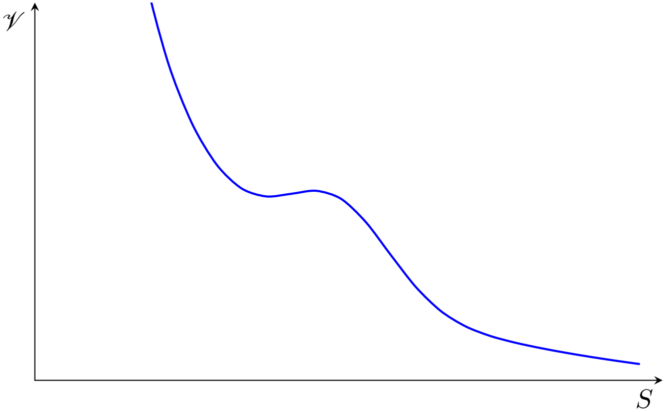

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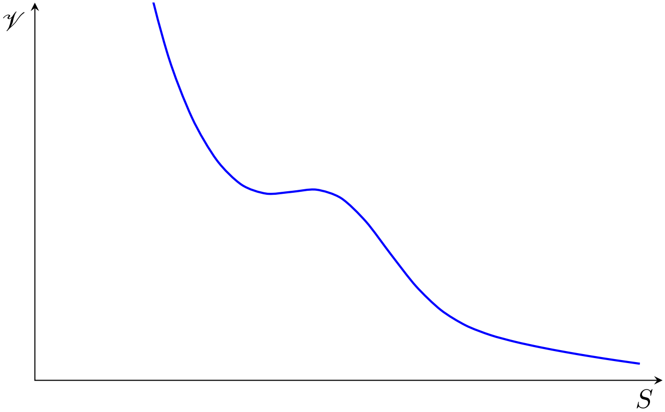

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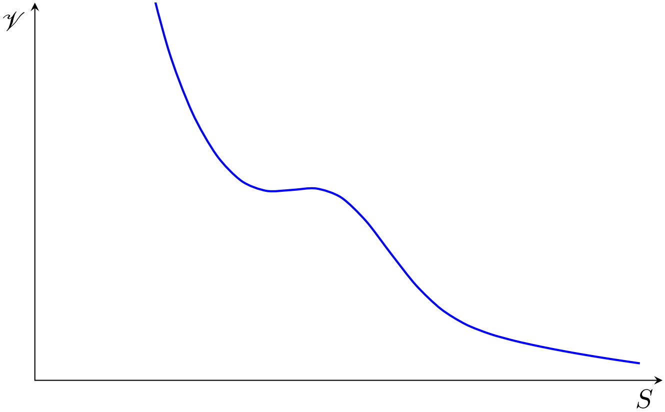

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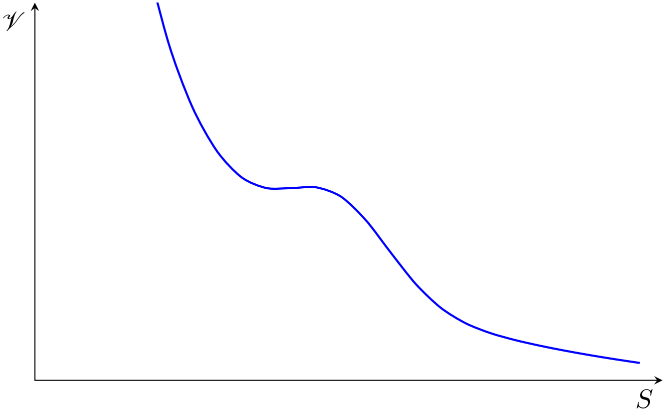

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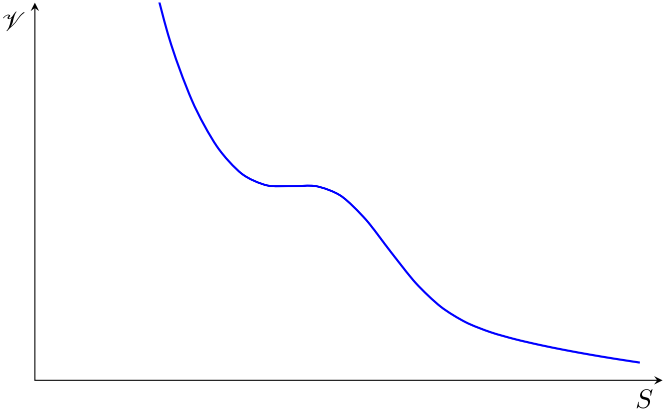

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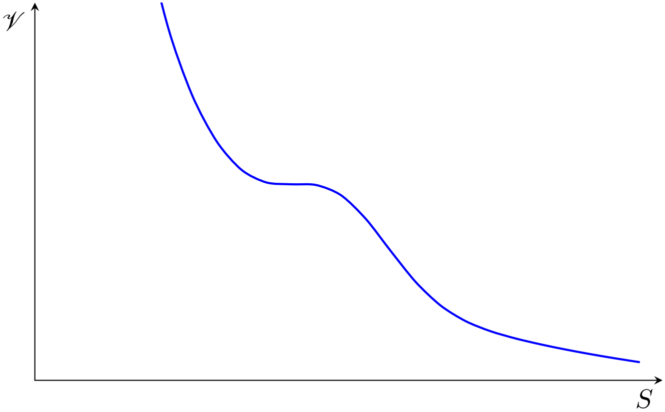

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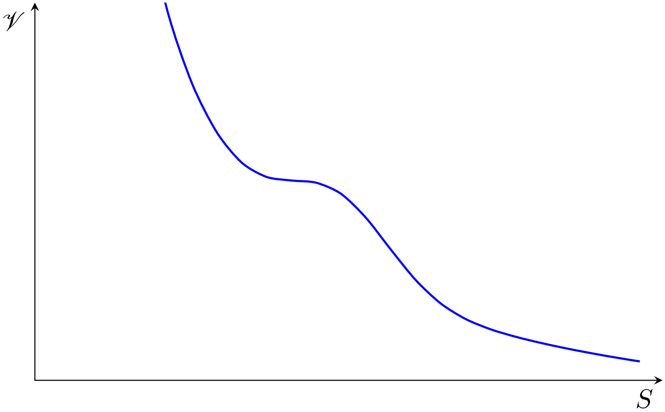

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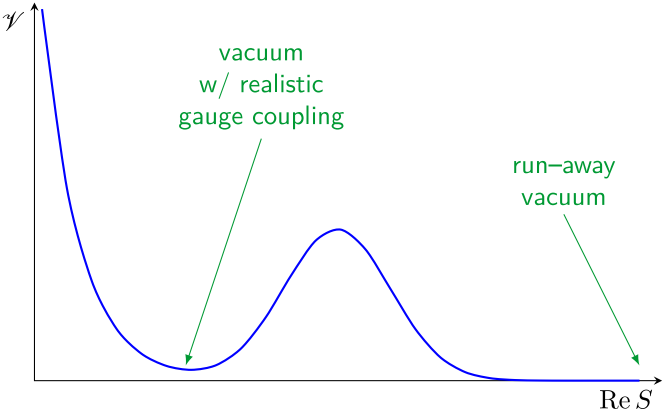

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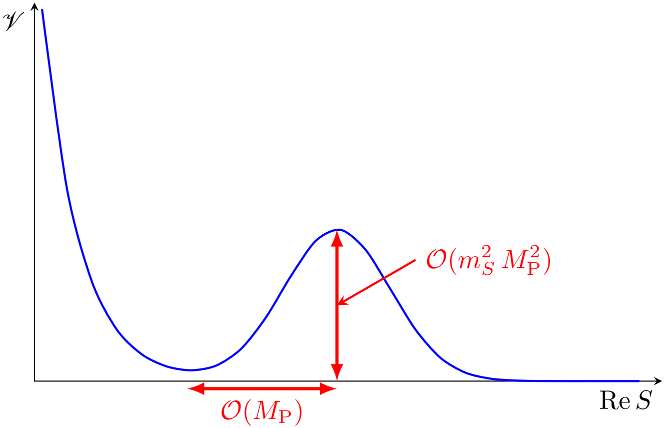

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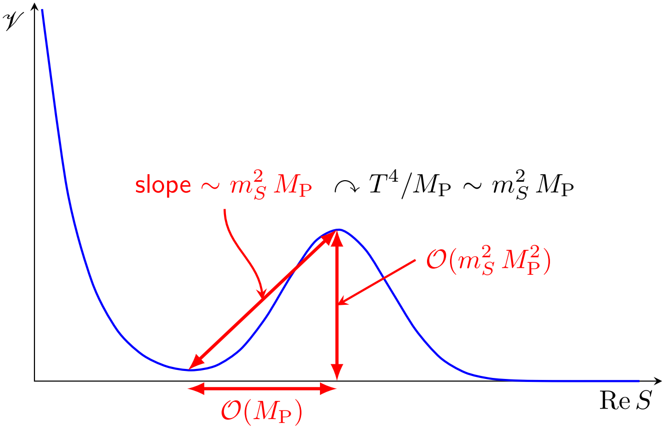

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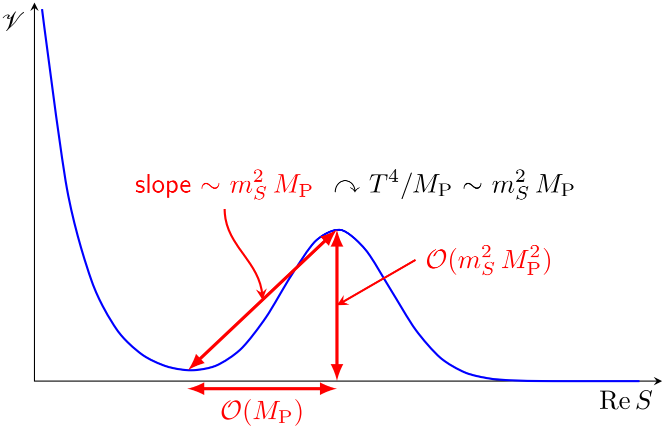

bottom–line:

critical temperature $T_* \sim \sqrt{m_S\, M_\mathrm{P}}$

Discussion

☞ if the dilaton has been destabilized, it will run away and cannot come back

model–independent contraint:

$$T_R \lesssim T_* \sim \sqrt{m_S\, M_\mathrm{P}}$$

reheating temperature (maximal temperature of the radiation dominated universe)

Discussion

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model–independent contraint:

$$T_R \lesssim T_* \sim \sqrt{m_S\, M_\mathrm{P}}$$

- model–dependent bounds on the energy density of the universe during inflation

Kallosh & Linde (2004)

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- ☞ model–dependent bounds on the energy density of the universe during inflation

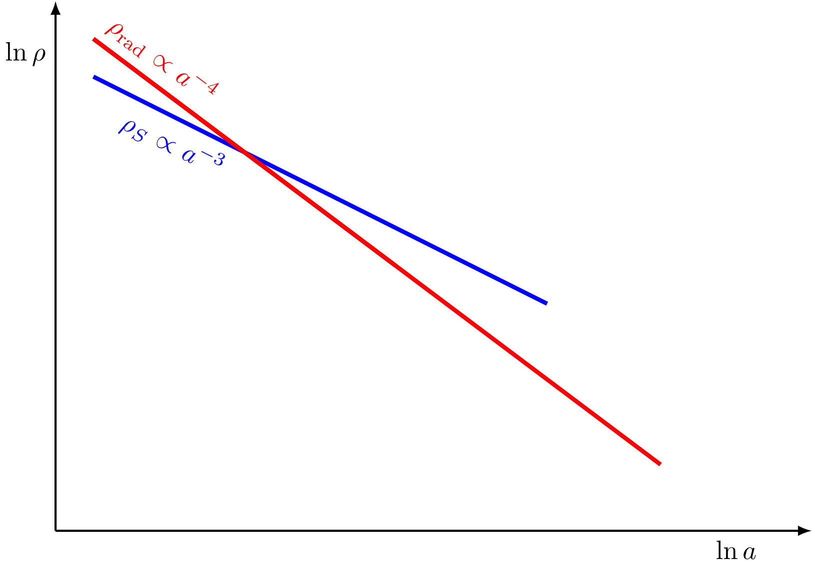
  Kallosh & Linde (2004)

- ☞ the bounds can be circumvented by stabilizing the field combination that fixes the gauge coupling in a different way (i.e. w/ an infinite barrier)

  Kane & Winkler (2019)

Moduli problems

Coughlan, Fischler, Kolb, Raby & Ross (1983); de Carlos, Casas, Quevedo & Roulet (1993),. . . ,
Cicoli, Conlon, Maharana, Parameswaran, Quevedo & Zavala (2023)



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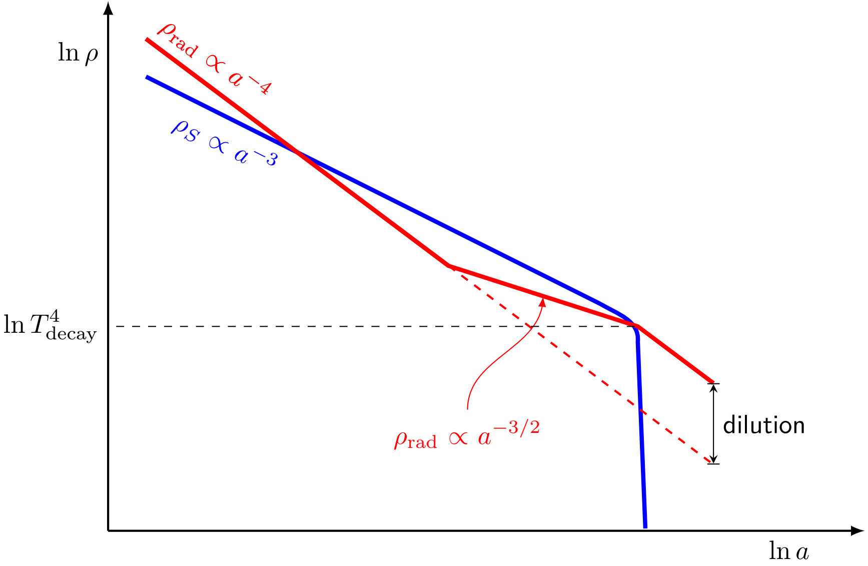

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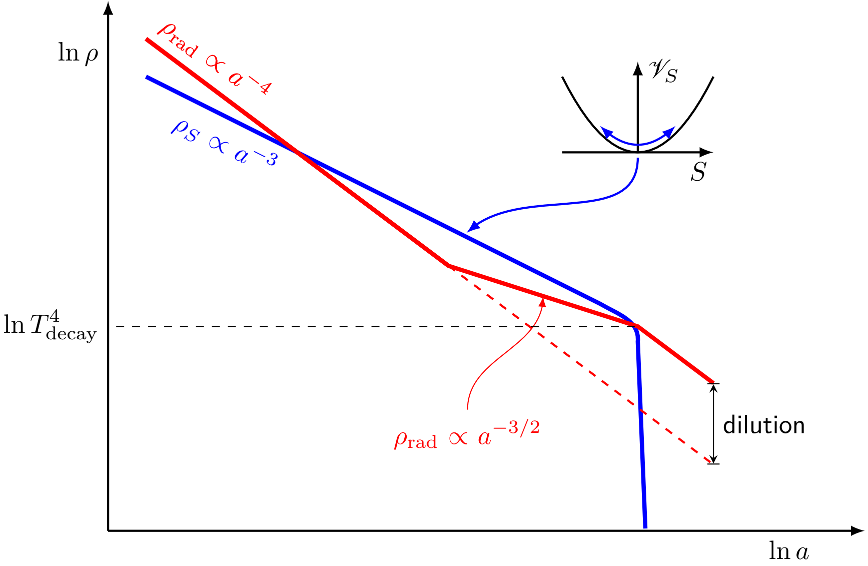

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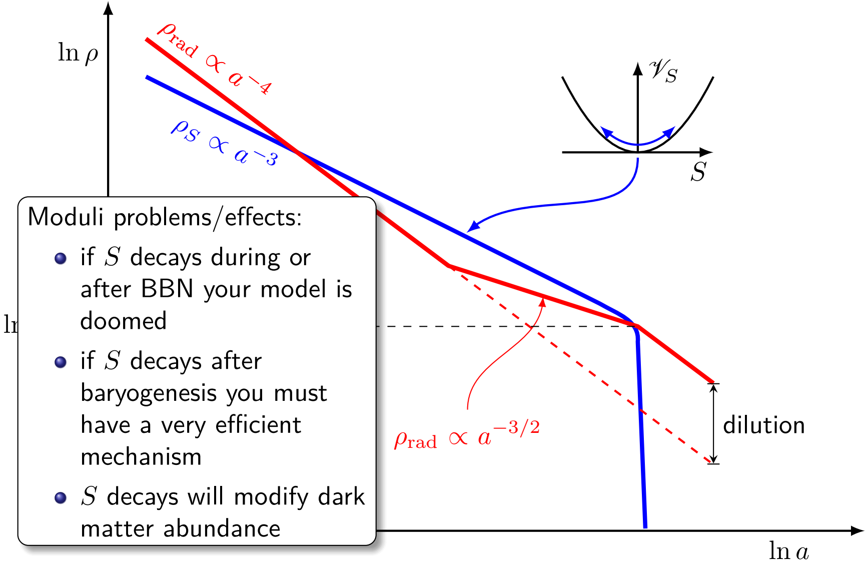

Moduli problems/effects:

- if S decays during or after BBN your model is doomed
- if S decays after baryogenesis you must have a very efficient mechanism
- S decays will modify dark matter abundance

Weight loss

solutions

Weight loss solutions

https://unsplash.com/

Weight loss solutions. . . in cosmology

https://unsplash.com/

main message

if masses and couplings of equilibrated particles depend on S, the dynamics of S will be such that the masses and couplings *decrease*

Weight loss solutions. . . in cosmology

https://unsplash.com/

main message

if masses and couplings of equilibrated particles depend on S, the dynamics of S will be such that the masses and couplings *decrease* i.e. the solution of the equations of motion entails weight loss

Constraints

on

flavons

Field–dependent fermion masses

☞ e.g. Froggatt–Nielsen mechanism

Froggatt & Nielsen (1979); see lectures by Mu–Chun Chen

$$\mathscr{L}_{\mathrm{FN}} = \sum_{i,j=1}^{3} y_{ij}^{u} \left(\frac{S}{\Lambda}\right)^{n_{ij}^{u}} \overline{Q}_i \, \widetilde{\Phi} \, u_j + \sum_{i,j=1}^{3} y_{ij}^{d} \left(\frac{S}{\Lambda}\right)^{n_{ij}^{d}} \overline{Q}_i \, \Phi \, d_j + \text{h.c.}$$

flavon

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- potential

$$\mathscr{V}_S = -\mu_S^2 |S|^2 + \lambda_S |S|^4 + \lambda_{S\Phi} |S|^2 |\Phi|^2 + \mathrm{U}(1)_{\mathrm{FN}} \text{ breaking terms}$$

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➥ VEV at $T = 0$

$$S = \frac{1}{\sqrt{2}}(v_S + \sigma + \mathrm{i}\,\rho)$$

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$$\alpha = \gamma\,\frac{\partial T_Y}{\partial \varepsilon} \sim 10^{-2}$$

- effective potential

$$\mathscr{V}_{\mathrm{eff}}(\sigma, T) = \gamma\, T_Y\, T^4 + \alpha\, T^4 \frac{\sigma}{\Lambda} + \frac{m_\sigma^2(T)}{2}\,\sigma^2 + \frac{\kappa}{3!}\,\sigma^3 + \frac{\lambda_S}{4}\,\sigma^4 + \dots$$

Modular flavor symmetries

Feruglio (2019); see lectures by Mu–Chun Chen

- more recent example: modular flavor flavor symmetries

$m \propto Y(\tau)$

- m: fermion mass matrix
- Y: vector-valued modular form
- τ: modulus

Modular flavor symmetries

Feruglio (2019); see lectures by Mu–Chun Chen

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- some couplings vanish at symmmetry–enhanced points

  Baur, Nilles, Trautner & Vaudrevange (2019);...; Feruglio, Gherardi, Romanino & Titov (2021);...; Feruglio (2023);...

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- more generally, the size of the couplings depends on τ
- many couplings vanish for $\operatorname{Im}\tau \to \infty$
- we could take e.g.

$$S = \operatorname{Im}\frac{\tau - \omega}{\tau + \omega}$$

$\omega = \mathrm{e}^{2\pi\,\mathrm{i}\,/3}$

Flavon dynamics

Lillard, MR, Tait & Trojanowski (2018)

☞ the flavon gets driven away from its $T = 0$ minimum until it gets stopped by the mass term or Hubble friction

$$\Delta\sigma \simeq -\alpha \frac{T^4}{\Lambda\, m_{\text{eff}}^2} \qquad \text{where } m_{\text{eff}}^2 = 6H^2 + m_\sigma^2$$

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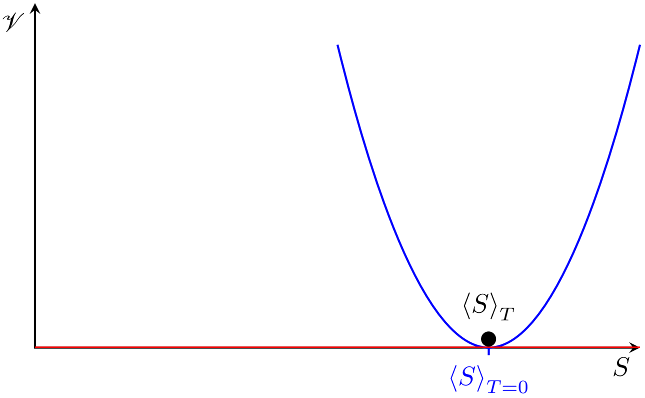
- as the temperature decreases, the flavon undergoes oscillations around the $T = 0$ minimum, which behave like nonrelativistic matter

Thermal flavon potential (cartoon)



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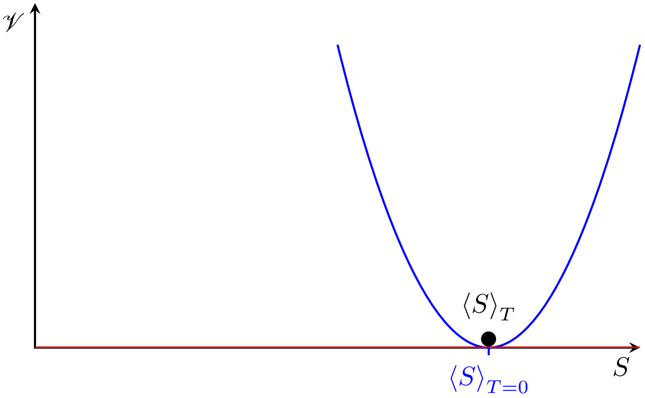

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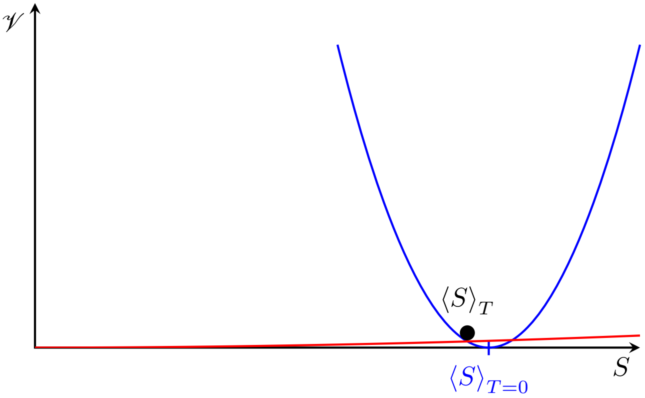

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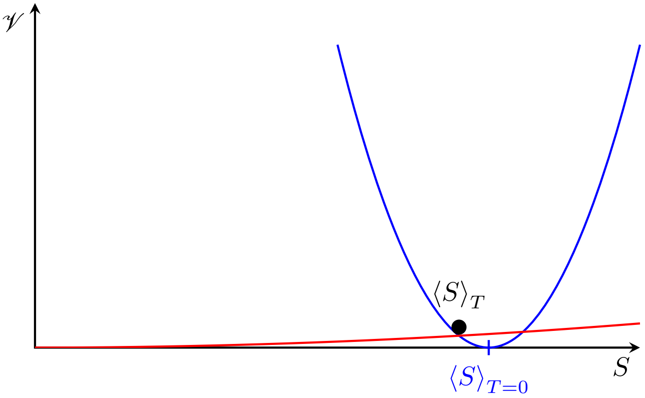

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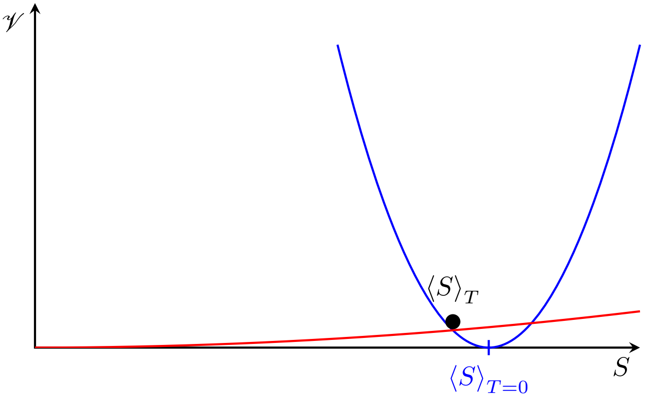

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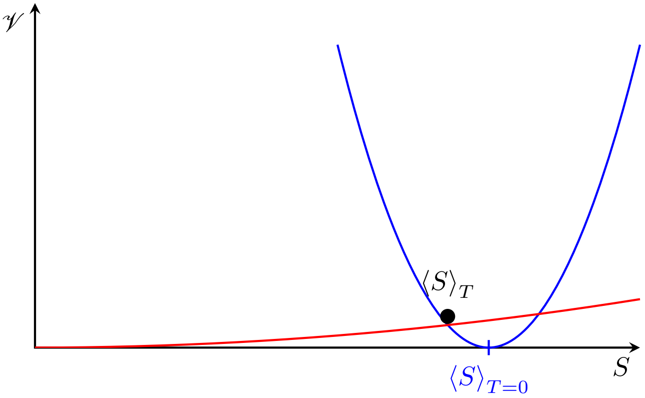

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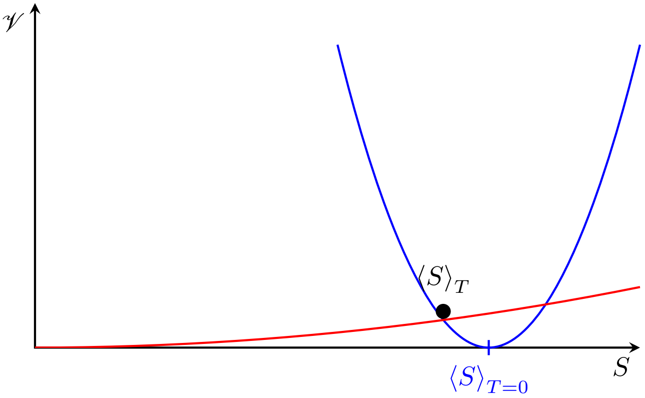

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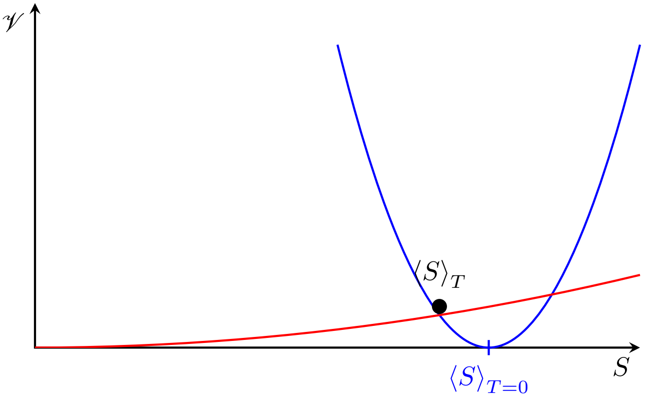

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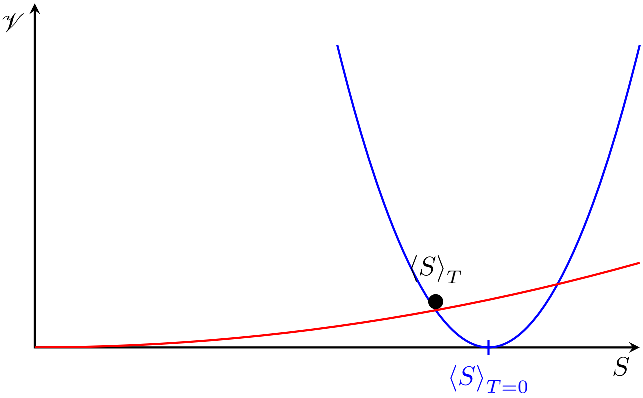

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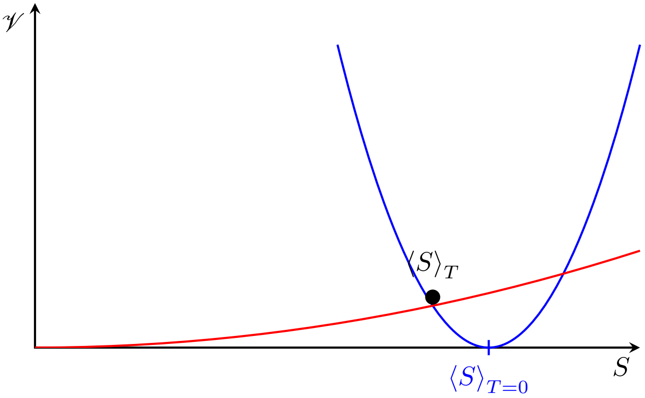

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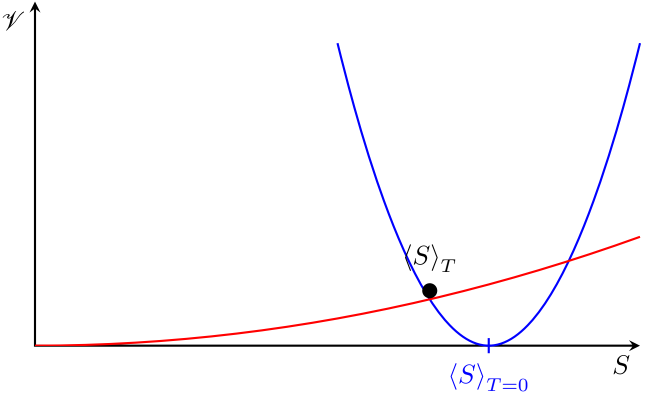

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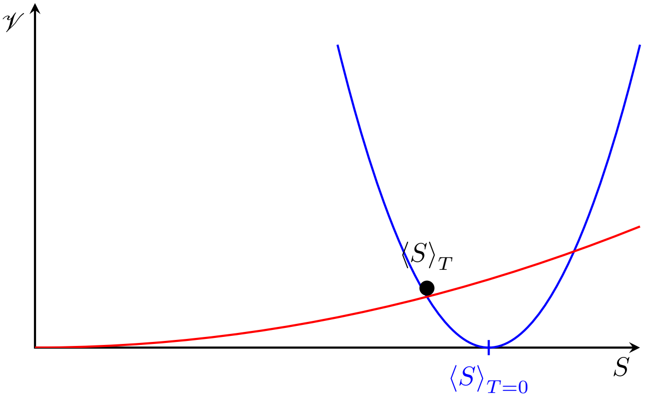

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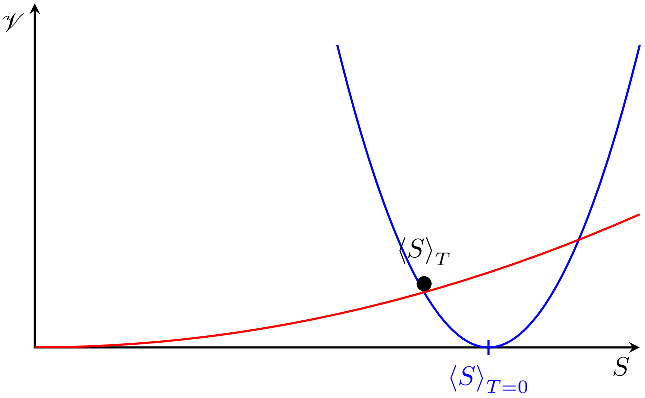

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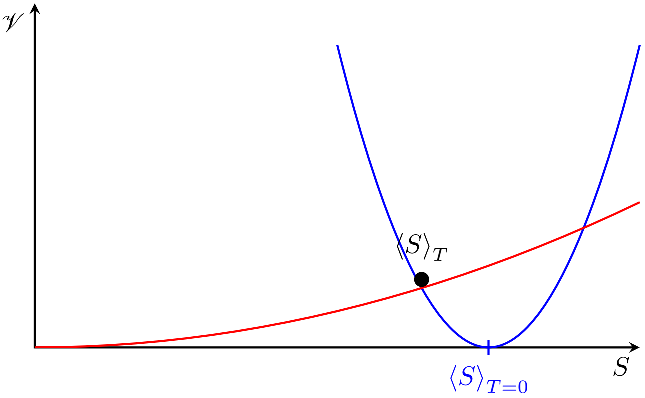

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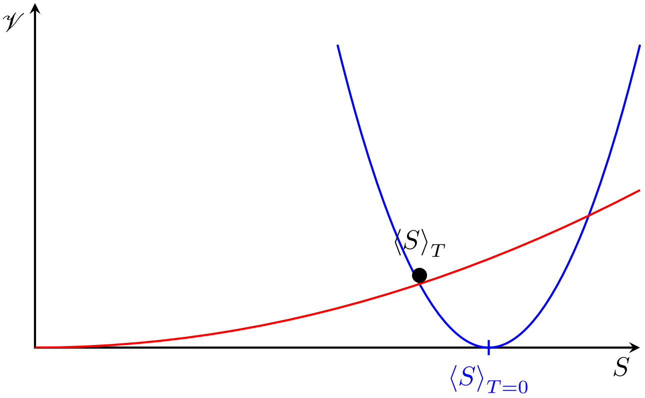

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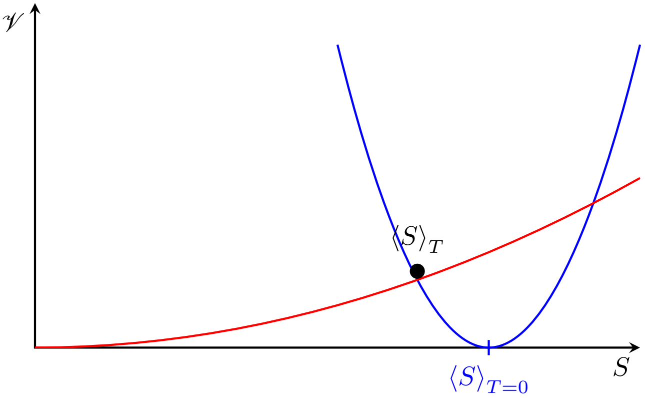

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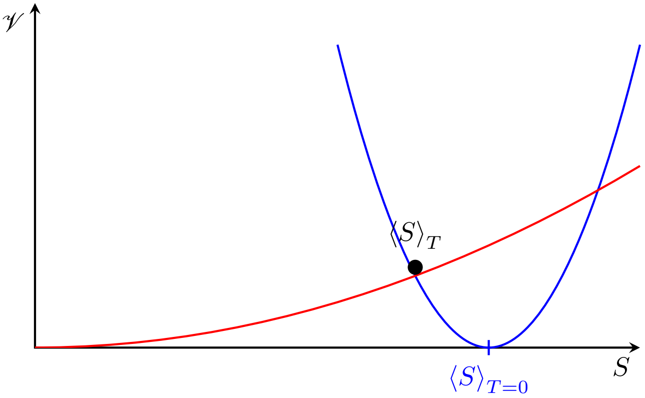

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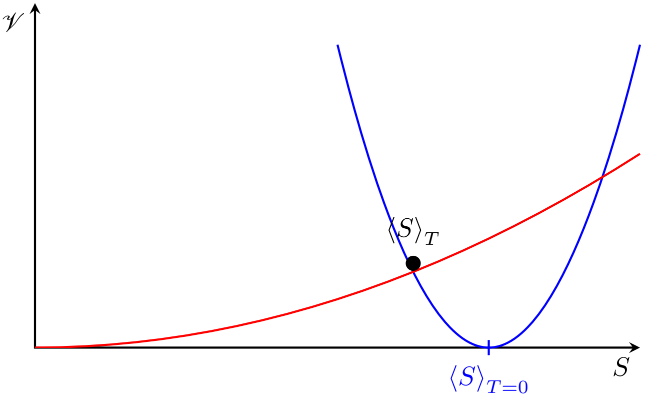

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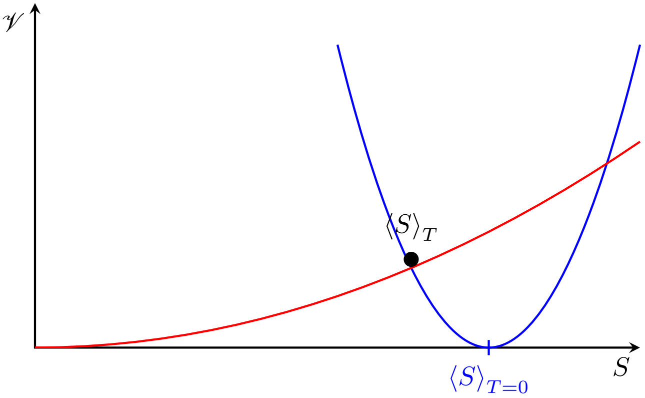

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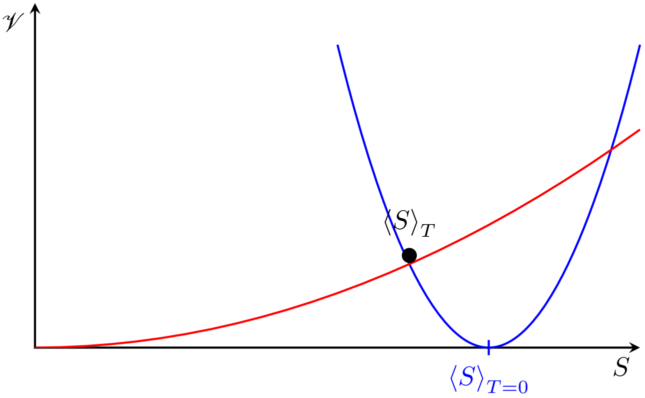

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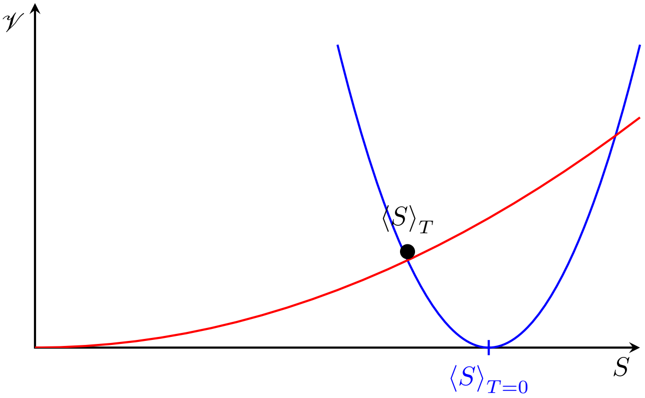

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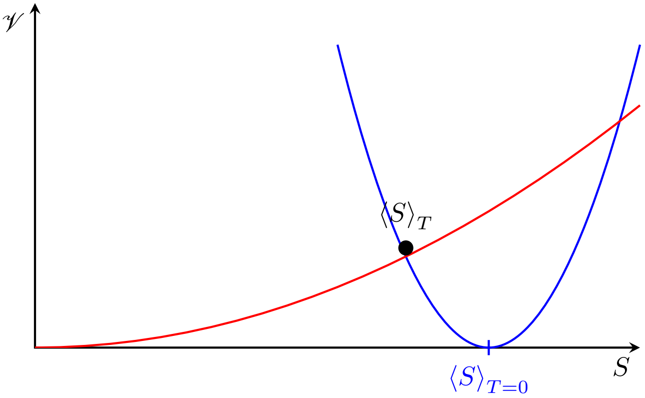

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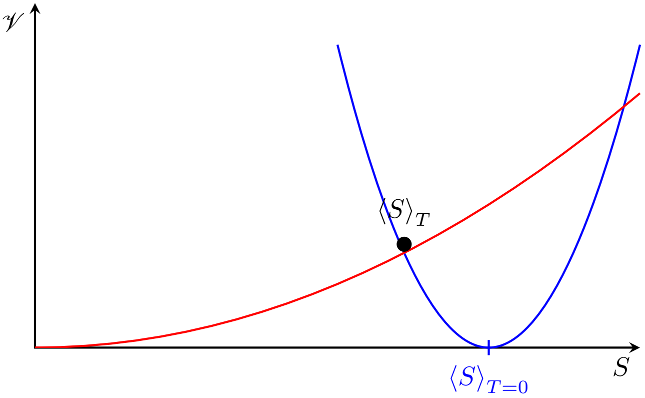

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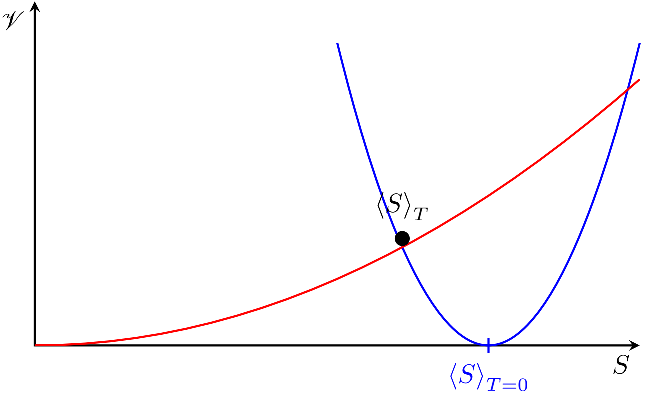

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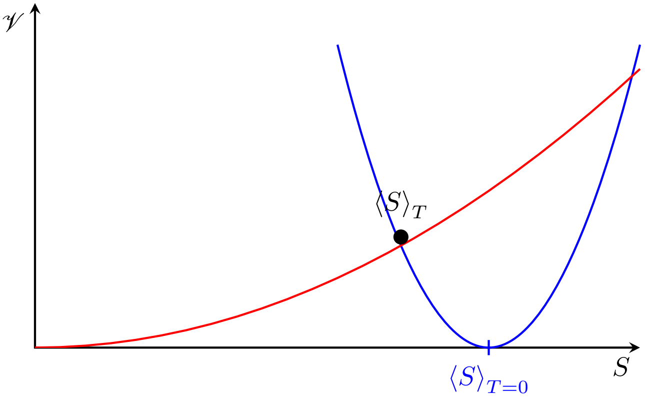

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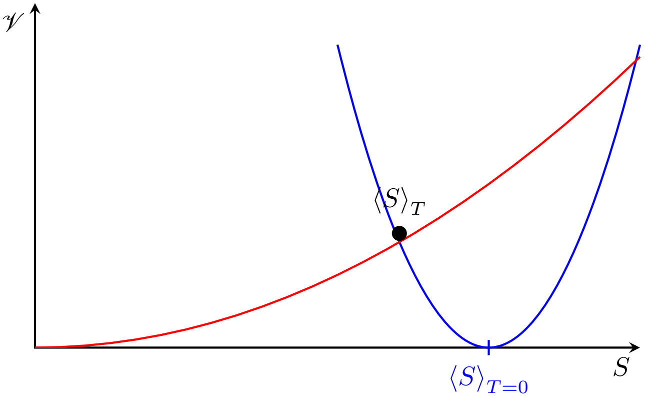

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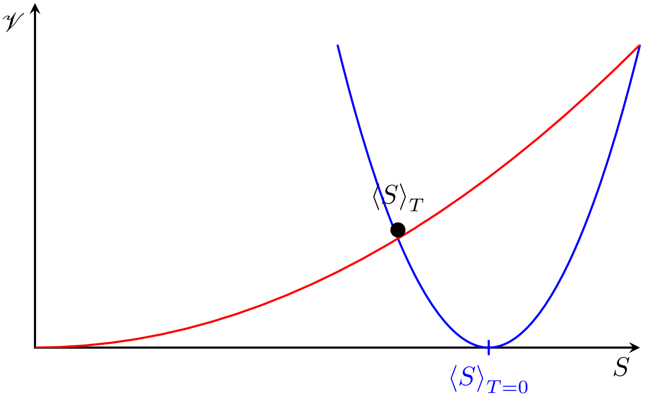

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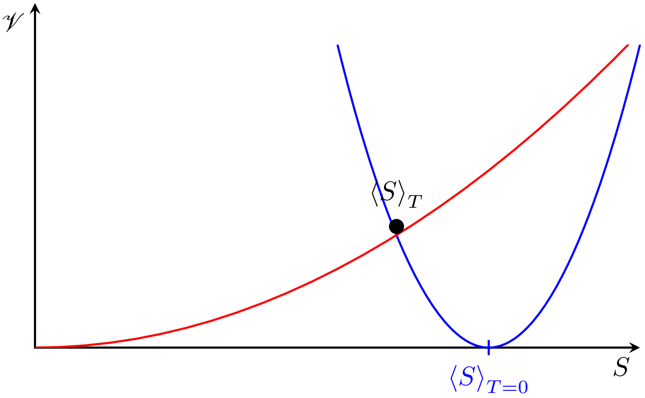

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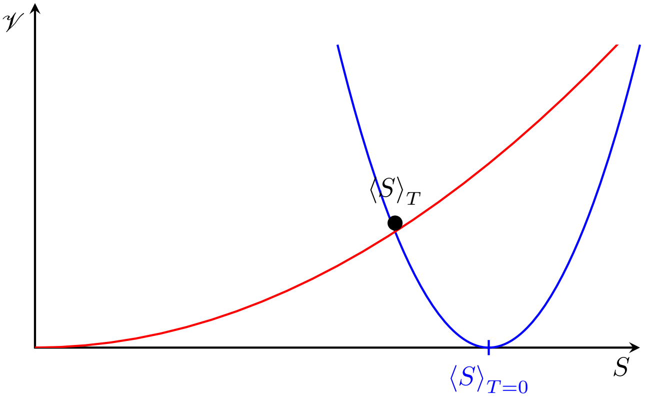

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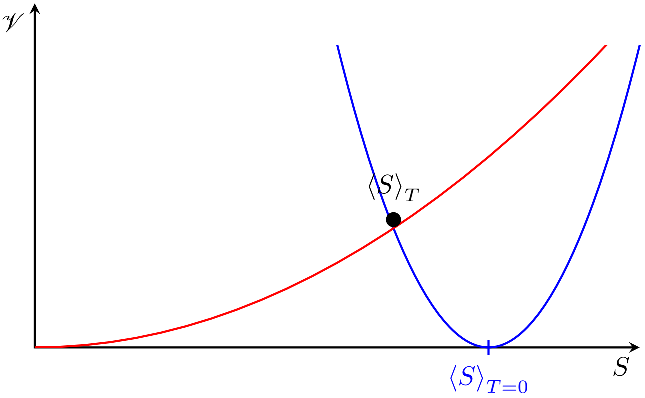

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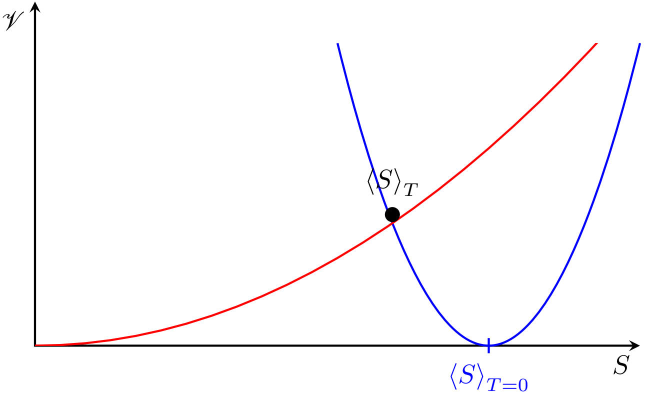

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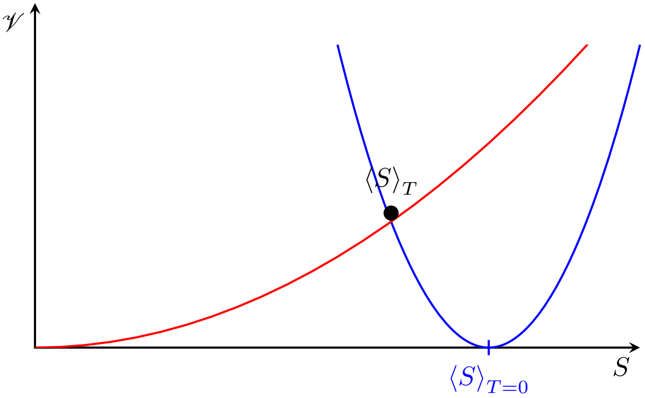

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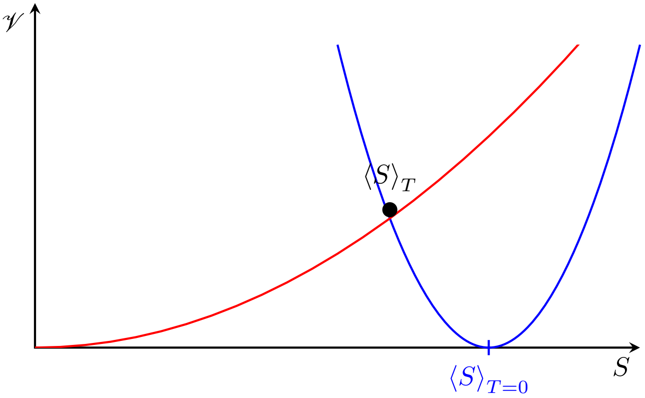

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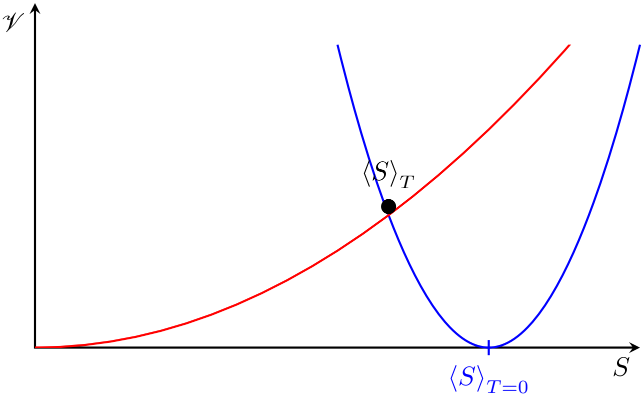

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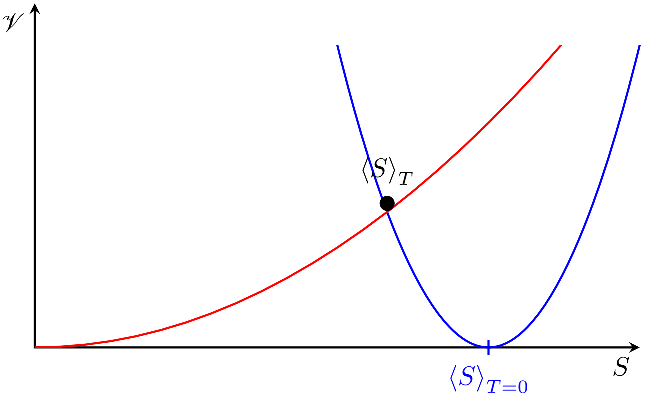

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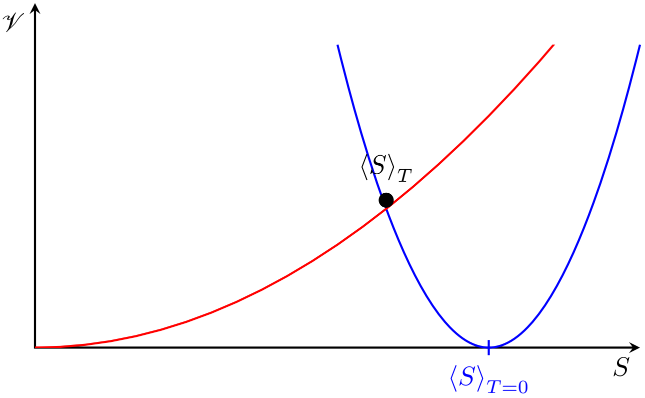

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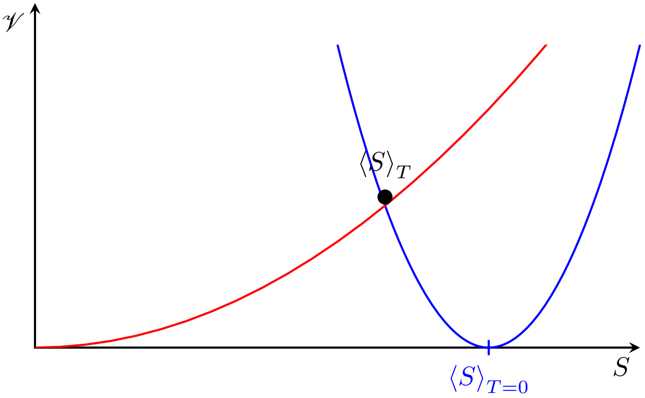

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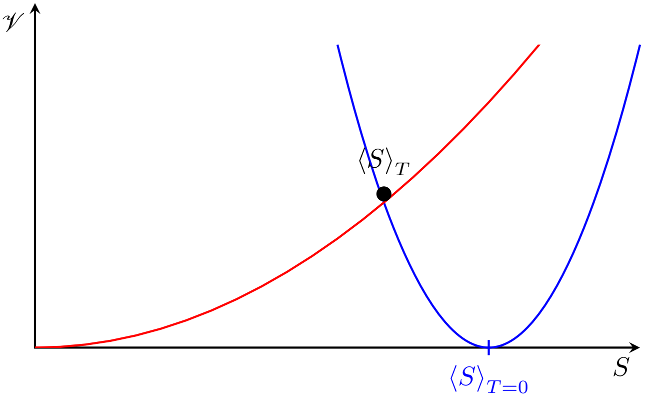

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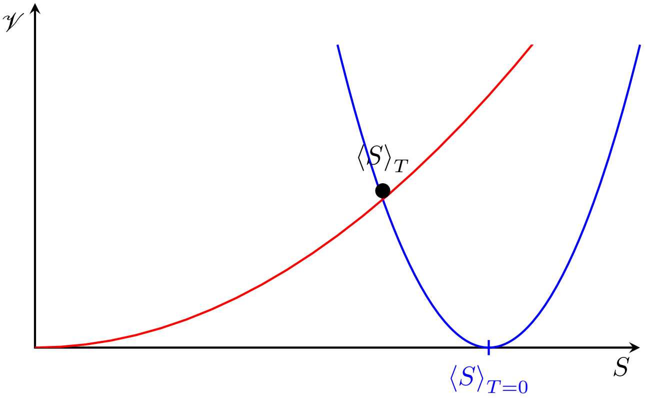

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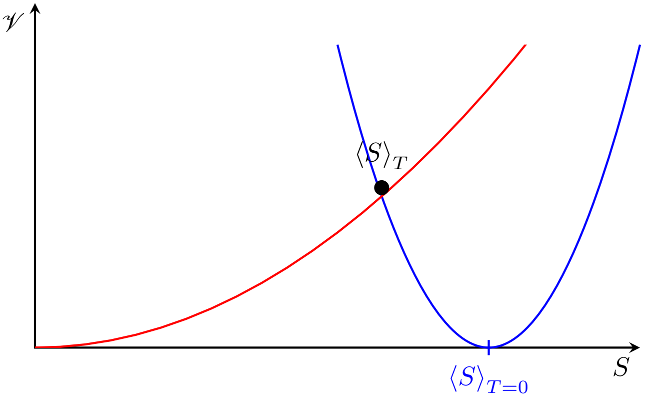

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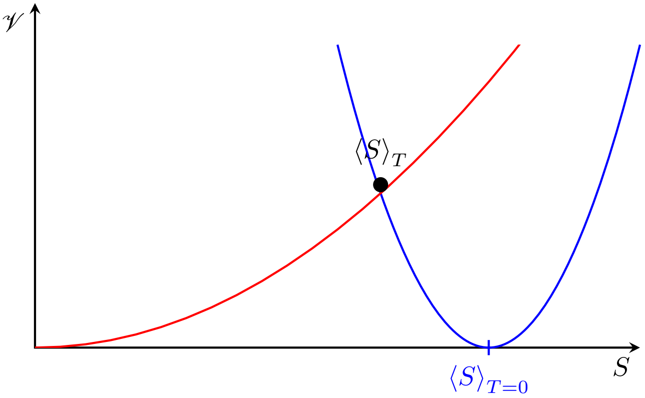

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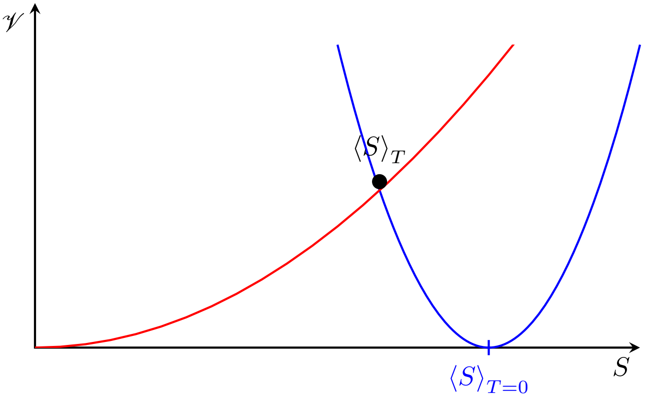

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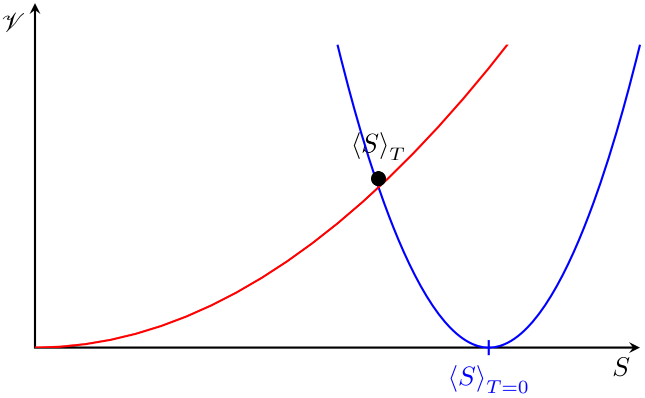

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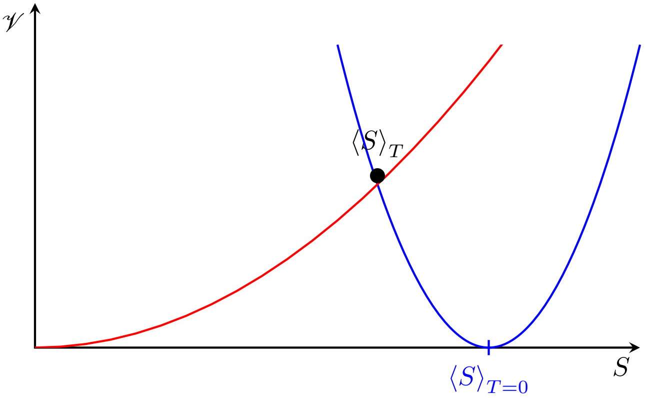

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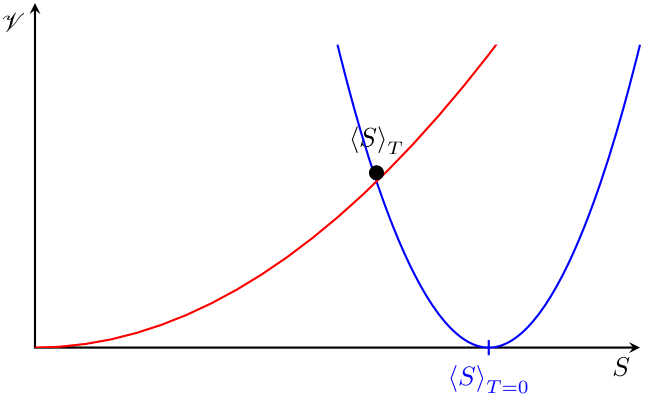

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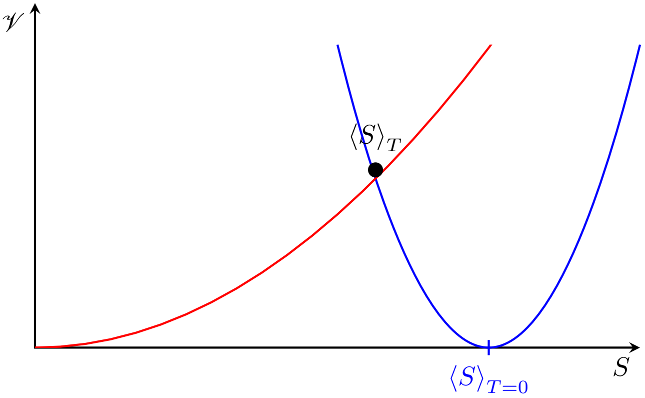

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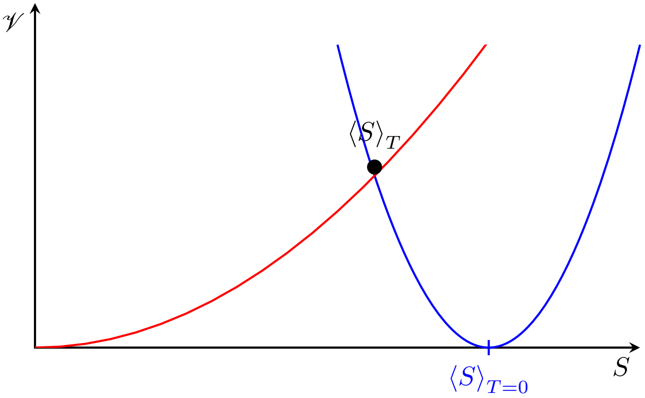

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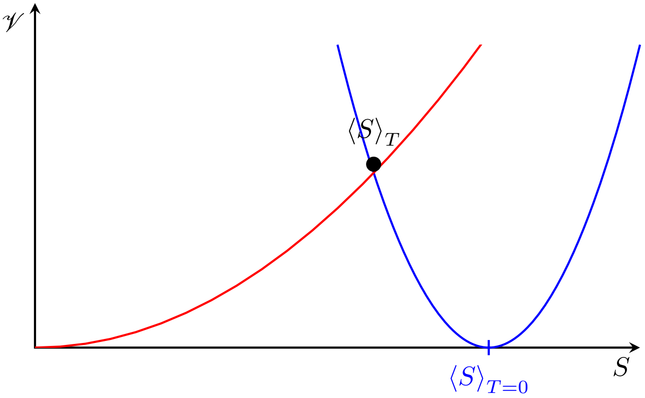

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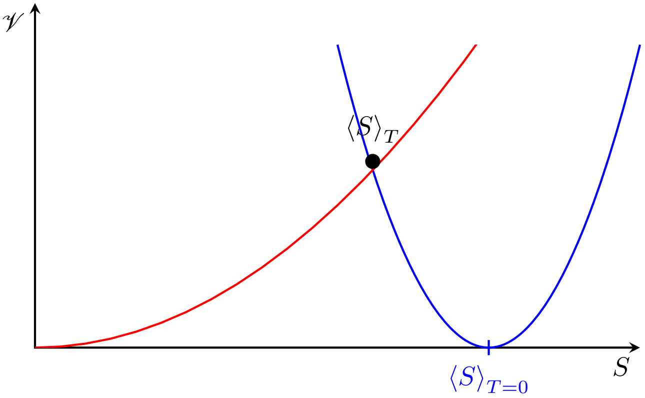

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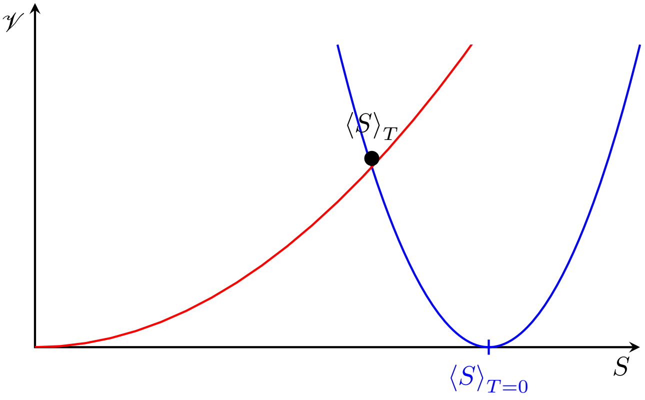

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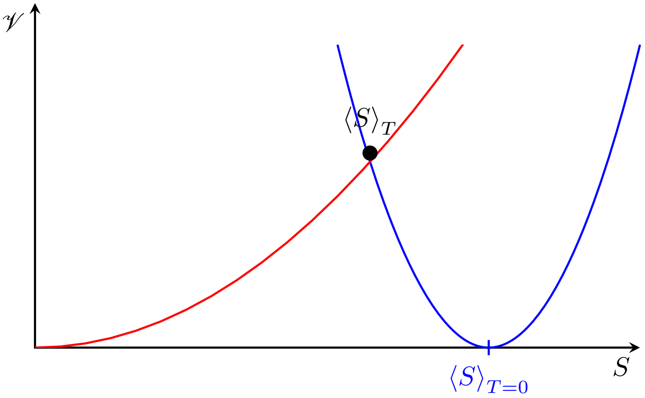

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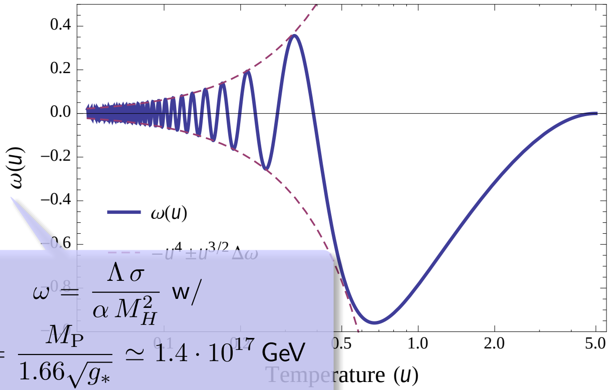

$$\omega = \frac{\Lambda\,\sigma}{\alpha\,M_H^2} \text{ w/}$$

$$M_H = \frac{M_\mathrm{P}}{1.66\sqrt{g_*}} \simeq 1.4\cdot 10^{17}\text{ GeV}$$

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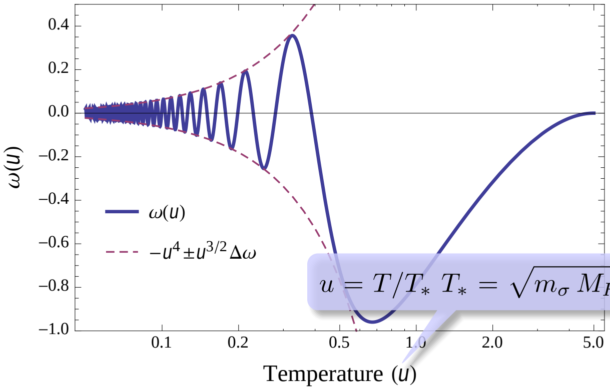

$u = T/T_*$ $T_* = \sqrt{m_\sigma M_H}$

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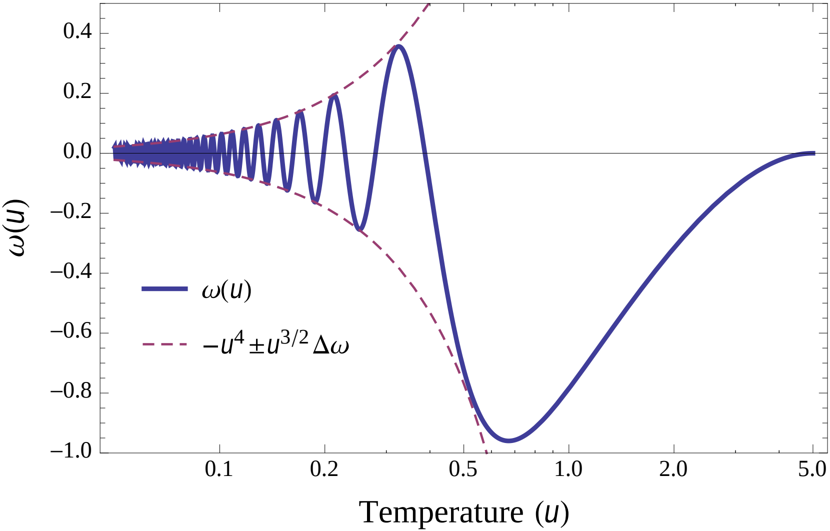

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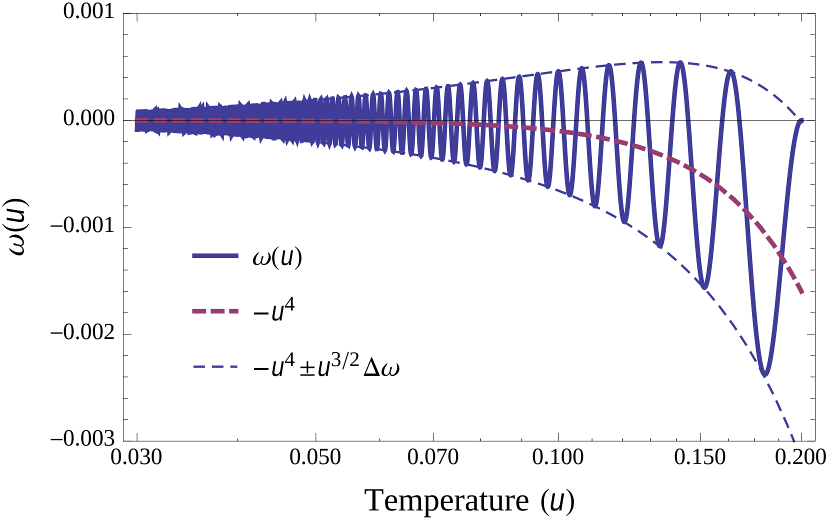

Moduli problems

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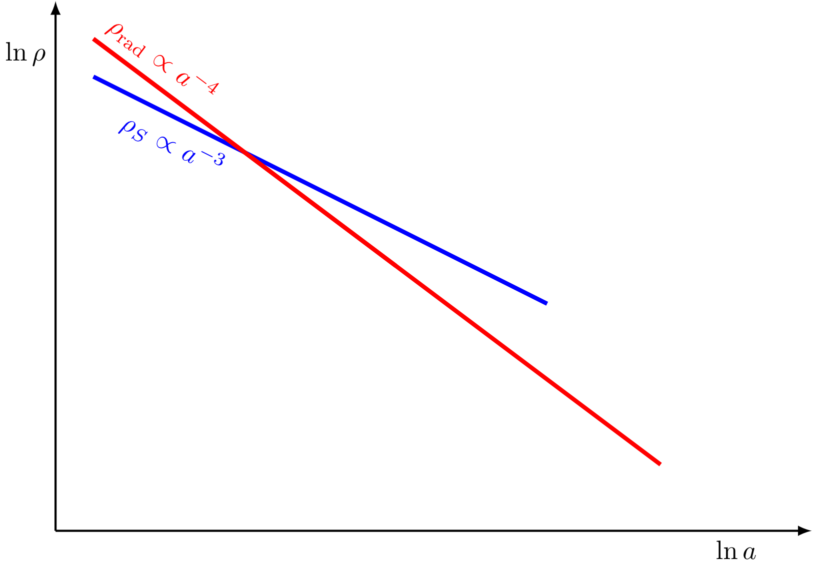

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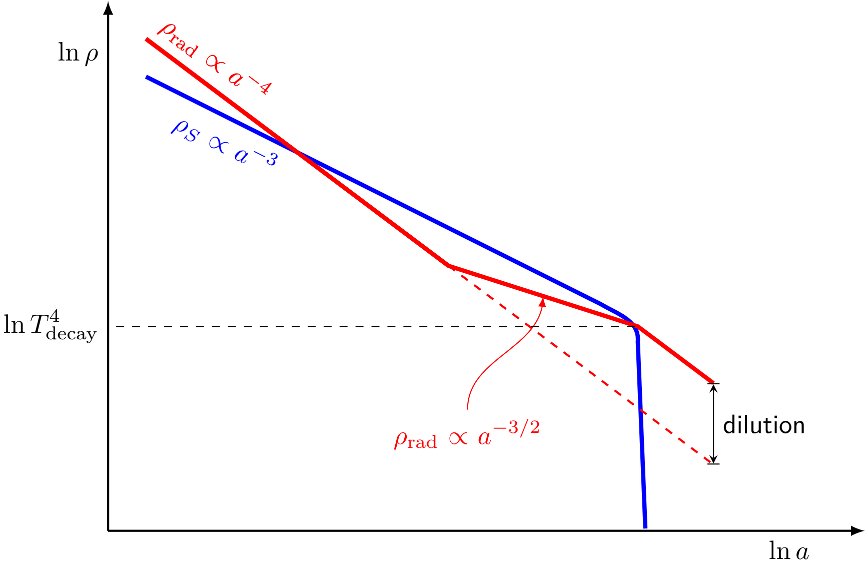

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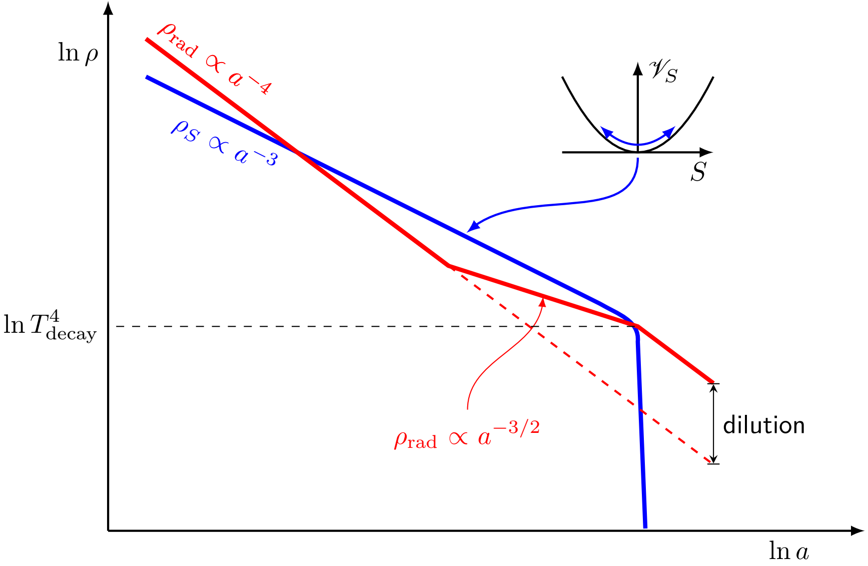

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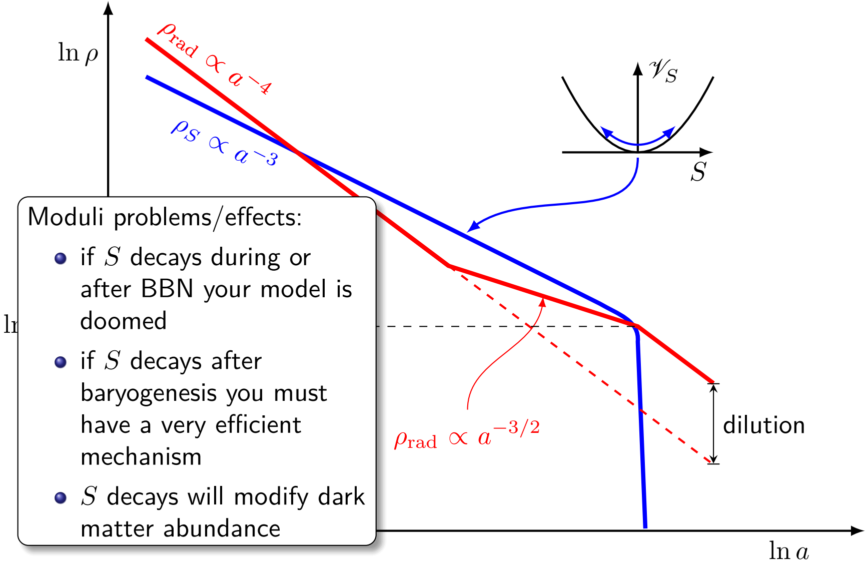

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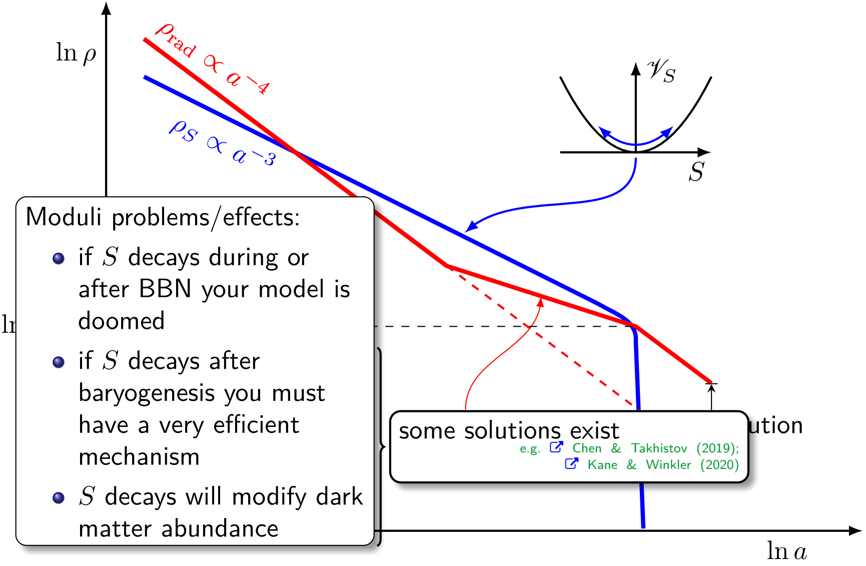

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some solutions exist
e.g. Chen & Takhistov (2019); Kane & Winkler (2020)

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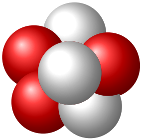

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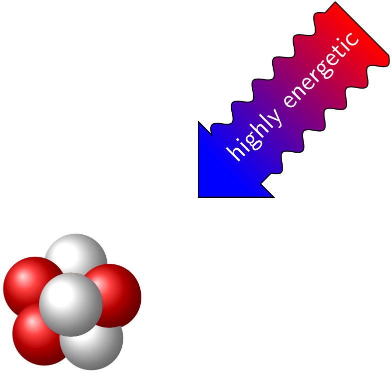

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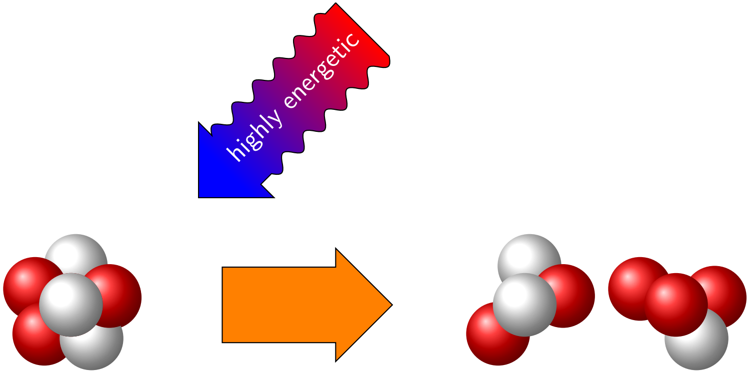

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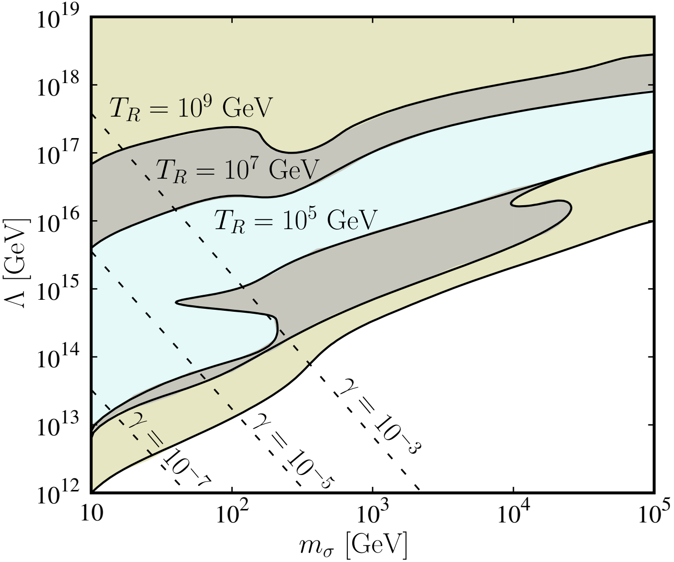

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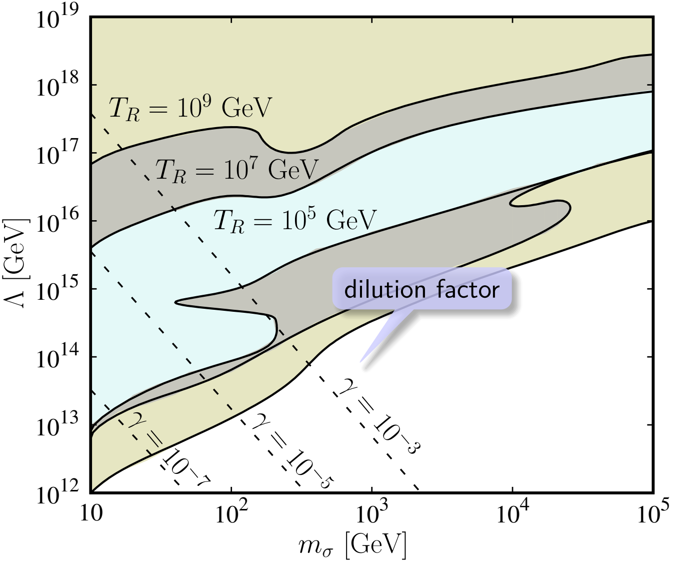

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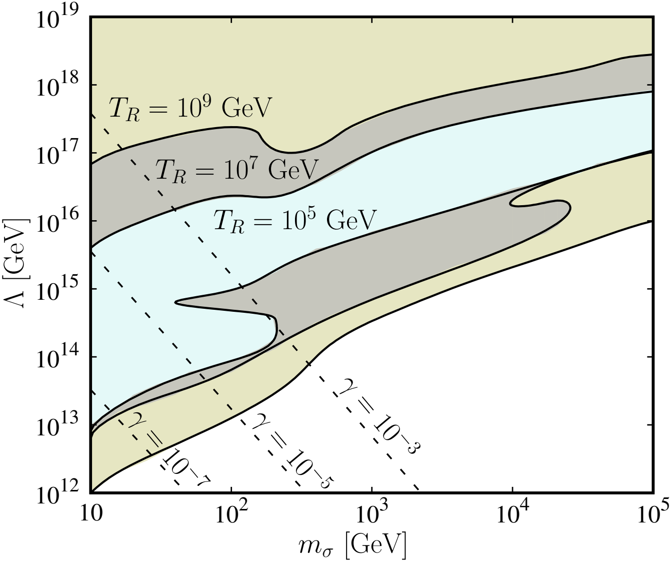

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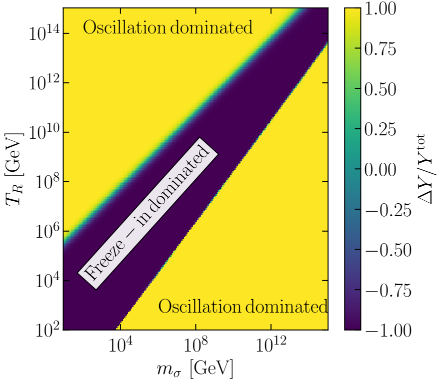

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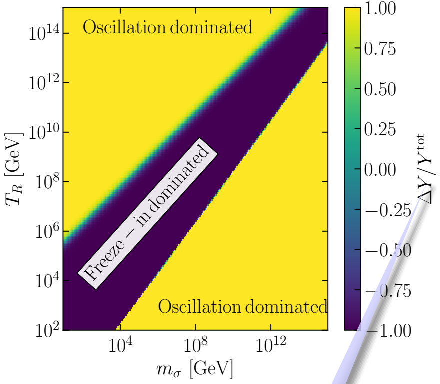

$$\Delta Y = Y^{\mathrm{osc}} - Y^{\mathrm{FI}}$$

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bottom–line:

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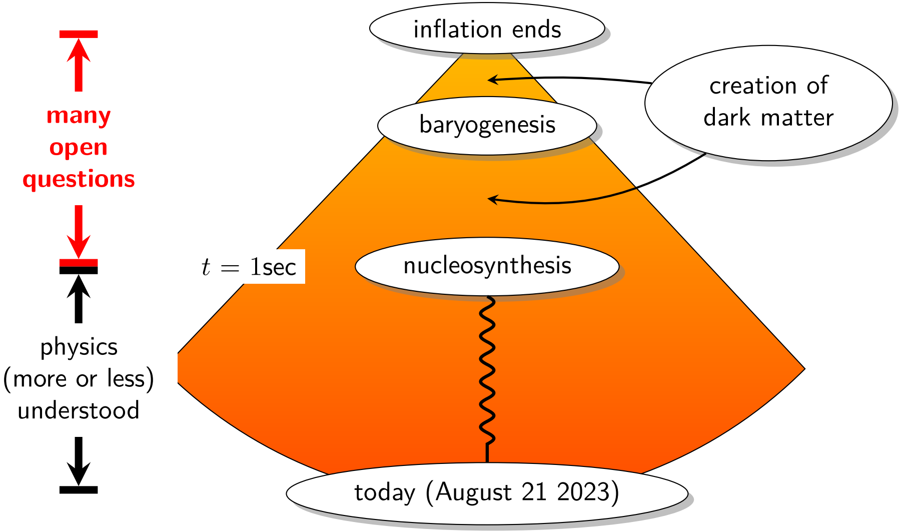
many
open
questions
physics
(more or less)
understood
inflation ends
baryogenesis
creation of
dark matter
$t = 1\text{sec}$
nucleosynthesis
today (August 21 2023)

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Thanks a lot!

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